Science & Global Security, 1999, Volume 8, pp. 41–98
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Technical Debate over Patriot Performance in the Gulf War*

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The performance of the Patriot PAC-2 theater missile defense system in the Gulf War sparked a prolonged public debate of unprecedented proportions. We review the technical dimensions of the debate over Patriot, concentrating on the two official Army studies of Patriot performance and the analysis of Patriot performance carried out by two MIT scientists using video tapes taken by the commercial news media during the Gulf War. We find there is an absolute contradiction between the Army scores for Patriot performance during Gulf War for all engagements and the scores based on the video data. We analyze in detail all of the technical challenges raised against the video analysis and find these challenges largely wanting. We conclude that the video tapes contain important information about Patriot performance in the Gulf War, and that the Army should have made use of the video information in its studies of Patriot performance. We identify three lessons from the Patriot debate that are likely to be applicable in the future conflicts where high technology weapon systems are being introduced into combat for the first time. Our study does not cover other U.S. theater missile defense systems, such as Patriot PAC-3/ERINT and THAAD.

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INTRODUCTION

The employment of the Patriot system in the 1991 Gulf War—the first use of a ballistic missile defense system in actual combat—drew extraordinary attention. Television news broadcast dramatic nighttime videos of Patriot-Scud engagements to an international audience. Media interpretations of the imagery appeared to confirm official statements of near-perfect performance. Renewed interest in ballistic missile defenses and increased public concern about the proliferation of ballistic missiles resulted.

Approximately 80 of all the Scud (Al-Hussein) missiles launched by Iraq during the Gulf War performed well enough to land in or near Israel or Saudi Arabia. The Patriot system "engaged" about 44 of these.[1] In Department of Defense parlance, the term "engaged" means the launch of one or more Patriot missiles against an incoming missile independent of success, that is, an engagement consists of one or more intercept attempts. Information in the public domain indicates that about 16 of the engagements occurred over Israel and about 28 over Saudi Arabia. Precise figures remain classified.

In the aftermath of the war, official Army performance statistics for the Patriot were revised downward in a series of stages: in March 1991 the overall success rate was reported as 96%; in May 1991 as 69%; and in April 1992 as 59%, the latter figure continuing as the official Department of Defense position on overall Patriot performance.[2]

In addition, serious questions began to be raised from outside of the Pentagon after the war about the actual success of the Patriot system. By the winter of 1991-92, a substantial public debate had emerged. In an attempt to resolve a growing controversy, the House Government Operations Committee (HGOC) then chaired by John Conyers (D-MI), held hearings on April 7, 1992.[3] The outcome of the hearings produced an even greater level of confusion, disagreement, and public acrimony over what seemed to many to be a relatively straightforward question of technical fact.

In response to the unsettled public debate, the Panel on Public Affairs (POPA) of the American Physical Society appointed an ad hoc panel in the spring of 1993 to look into the technical questions at the core of the debate over the Patriot. This article describes what the members of the ad hoc panel learned about the Patriot debate in the course of their investigations together with the results of follow-up studies of certain technical issues. Appendix A provides a brief chronology of the panel's work.

The ad hoc panel conducted all of its work at the unclassified level. This was made possible by several factors: (1) the HGOC hearings were public; (2) General Accounting Office (GAO) and Congressional Research Service (CRS) reviews of the Army studies are unclassified, although the reviews were carried out with full access to the classified database and study methodologies; (3) general information about the Army methodology is public; (4) all challenges to official Army reports of Patriot performance are based on unclassified data; and (5) none of the officials or organizations involved in the Patriot debate—including the Army—have ever claimed that they needed to go into closed (classified) session to explain their findings.

Because the Army studies remain classified, there was an asymmetry in the panel's work and this article reflects that fact. The panel reviewed all of the technical aspects of the Army studies that are in the public sector as well as all of the technical aspects of the most comprehensive challenge to the Army's findings. The panel, however, did not perform an independent analysis of the performance of the Patriot in the Gulf War. When and if further details of the Army's analyses are declassified, e.g., the Army scores for individual Scud engagements, useful further work and more detailed comparisons can be made.

Patriot ground control units employed in the Gulf War were not routinely operated with data-recording devices apparently out of concern that such devices might cause system malfunctions. Consequently, continuous records of radar and system information during engagements and the trajectory and operational data needed to make highly detailed analysis of Patriot-Scud engagements do not exist. (Many air defense radars have built-in recording systems as standard equipment, but this was not the case for the Patriot.) In a few cases, the Israelis attached recording devices to Patriot ground-control units during actual operations. However, this occurred only late in the war and the amount of data collected was meager. No analogous recordings were collected in Saudi Arabia. In spite of the lack of good technical data, a great deal of effort has been expended to determine Patriot performance in the Gulf War because that experience is more realistic and greatly exceeds in volume anything that could ever be created at a missile test range.

THE PATRIOT SYSTEM

The Patriot is an Army surface-to-air missile system that began development as an antiaircraft weapon in the late 1970s; it was first deployed in 1982.[4] In the late-1980s, the system was modified to give it the capability to intercept short-range ballistic missiles. This first modification, called PAC-1 (Patriot Anti-tactical-missile Capability), consisted of software changes to the guidance radar, which gave the system the capability to track and intercept several short-range ballistic missiles simultaneously. A later, second modification

(PAC-2) gave the missile warhead a new fuse and heavier fragments to improve its kill capability against ballistic missiles. At the time of the Iraqi invasion of Kuwait in August 1990, only a handful of PAC-2 missiles existed in the U.S. inventory. In response, production of the PAC-2 interceptor was dramatically surged (three around-the-clock shifts, seven days a week) to meet the anticipated requirements of the impending war.

The Patriot interceptor missile used in the Gulf War is powered by a single-stage solid-propellant rocket motor and achieves a burnout velocity of Mach 5 (1.5 km/s) about 12 seconds after launch. The interceptor is 5.33 m long, weighs 1,000 kg, and has a range of approximately 60 km. The missile is armed with a warhead consisting of 45 kg worth of 50-g pellets driven by 40 kg of high-explosive and detonated by a self-contained radar proximity fuse.

A Patriot Battery, the basic unit of the system, consists of a C-band phased-array ground-based radar used for both surveillance and tracking, a ground control station for command and control of the interceptor missiles, and eight launchers. Each launcher contains four PAC-2 interceptor missiles.

The brain of the system is its weapons-control computer,[5] which performs the system's core functions of acquiring and tracking incoming targets, guiding interceptors to targets, and other battle-management functions. The Patriot system employs a track-via-missile guidance scheme in which the target and interceptor are jointly tracked by the Patriot radar. In addition, radar signals reflected from the target and received by the interceptor are relayed back to the ground control station via a data link for processing; commands are then sent back to the interceptor to guide it to its target. The basic system strategy is to put the Patriot interceptor on the reverse trajectory (anti-trajectory) of the incoming target missile. If all goes well, the Patriot interceptor ultimately acquires its target by means of a self-contained fusing radar and, at the optimal moment determined by electronics in the interceptor, the Patriot warhead is "fused" (detonated). As a safety feature, a Patriot interceptor that fails to acquire a target via its fusing radar in the designated time window for intercept, sacrificially fuses after a prescribed delay.

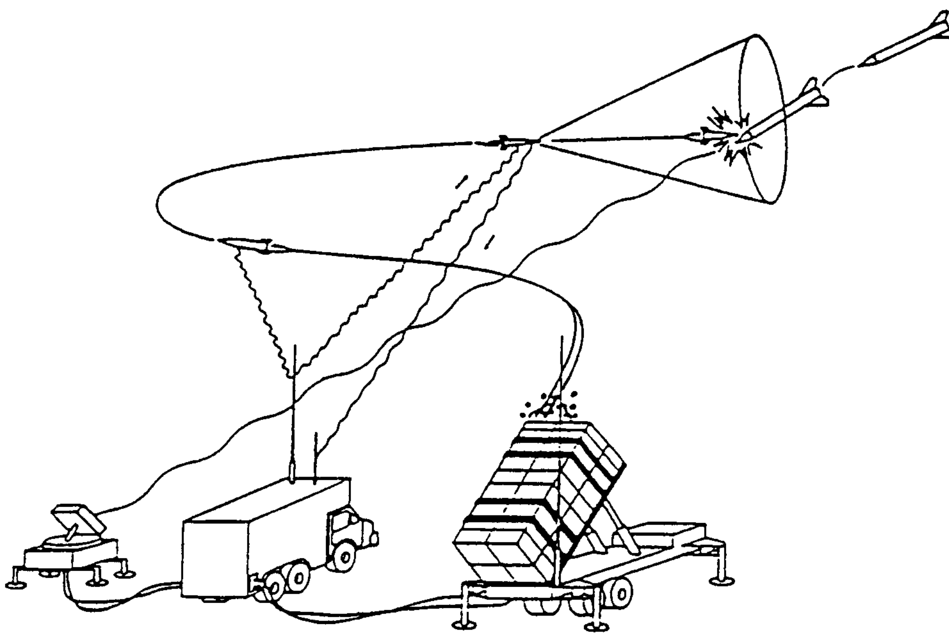

Figure 1: Schematic of the Patriot PAC-2 ballistic missile defense system used in the Gulf War. Each Patriot Battery consists of a C-band phased array radar for tracking both the incoming missiles (Scuds) and outgoing Patriot interceptors; a ground control station that processes the return signals from the Scuds and Patriot interceptors and computes trajectory corrections, which are uplinked to the interceptor; and eight Patriot launchers (only one shown), each of which carries four interceptor missiles. Note that the interceptor trajectory is incorrectly shown; the interceptor actually files out a certain point and then turns and flies up the anti-trajectory of the Scud making the intercept attempt nearly head-on. (Figure courtesy of Hildreth and Zinsmeister.)

AL-HUSSEIN MISSILE

The Al-Hussein missile employed by Iraq during the Gulf War against Israel and Saudi Arabia was a modification of the Soviet Scud B, a single-stage liquid-fueled short-range tactical missile (there is no separable reentry vehicle). The standard Scud B has a launch weight of about 6,000 kg, a length of approximately 11 m, and is capable of delivering a 1,000-kg warhead to a range of about 300 km. To increase the range of the missile to approximately 600 km, the warhead was reduced to about 300 kg and the lengths of the fuel tanks increased, resulting in a missile with an overall length of 12.2 m and a launch weight of 7,000 kg.[6] Appendix B gives a summary of the parameters of the Al-Hussein. For simplicity, we will hereafter refer to the Al-Hussein as a "Scud."

The Iraqi modifications of the Scud B resulted in a missile that typically broke up during reentry, with the warhead section (warhead and possibly attached portions of the missile body) followed by a stream of debris.[7] One or more of a number of factors could have contributed to this breakup: (i) the Al-Hussein's reentry velocity is considerably higher than that of the normal Scud B, and so the aerodynamic forces experienced by the modified missile are much greater; (ii) the increased length and lighter payload causes the center of gravity of the missile to shift backward, making it less aerodynamically stable; and (iii) the Al Hussein may have reentered the atmosphere with a large angle of attack (angle between the body symmetry axis and velocity vector), a configuration that leads to high lateral stresses on the missile body as aerodynamic forces build up.

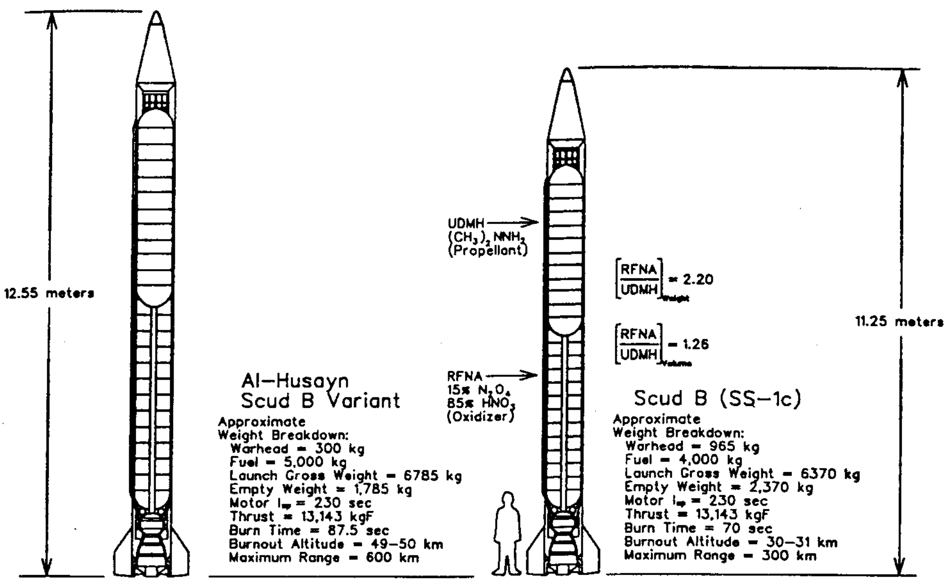

Figure 2: Comparison of the Soviet designed Scud B missile and the Iraqi Al-Hussein, which has approximately twice the range. The greater range is achieved by reducing the high-explosive payload by two-thirds and extending the fuel (unsymmetrical di-methyl hydrazine) and oxidizer (red fuming nitric acid) tankages by 20 percent. (Figure courtesy of Postol and Lewis.)

TECHNICAL ANALYSIS OF PATRIOT PERFORMANCE

There have been to date six technical analyses of Patriot operations in the Gulf War in which a systematic attempt was made to collect and evaluate data bearing on the overall performance of the system in one or both countries of operation. Four of these estimated an overall success rate for the Patriot. Of these, two are official studies done by the U. S. Army; the third is a study done by the Israeli Defense Forces (there may have been additional studies); and the fourth is a study done by two MIT researchers using videotapes taken by the TV news media of Scud engagements over Israel and Saudi Arabia during the war. The two other technical studies each looked at ground damage and casualties in Israel before and after the introduction of the Patriot. All other commentary on the overall Gulf War performance of the Patriot—and it is extensive indeed—consists of reviews of these studies, summaries or criticisms of one or more of the six analyses, or discussions of issues distinct from the Patriot performance.

The two official Army analyses of Patriot Gulf War performance were carried out post war by the Patriot Program Office with technical support provided by Raytheon Company, the prime contractor for the Patriot system.[8,9] Official scoring of Patriot-Scud engagements in these studies was done by teams of Army officials. The studies were based on available technical data from ground control units together with data from inspections of Scud impact craters. Results from the first Army study were reported publicly in December in 1991.[10] The results of the second Army study were first reported at the April 1992 HGOC hearings. The data and the reports associated with both studies remain classified.

During the Gulf War, the Israelis conducted quick-response studies in an attempt to understand Patriot performance and to reduce wastage of interceptors on nonlethal debris resulting from Scud breakup. No information has yet been officially released by the Israeli government about its studies of Patriot performance during the Gulf War. However, over time some information about the conclusions of these studies has become publicly available.

An Israeli reporter of defense and military affairs (and retired Israeli Air Force pilot) Reuven Pedatzur testified at the 1992 HGOC hearing concerning what he learned in interviews with Israeli officials about data collection and analysis done in Israel during the war concerning the performance of the Patriot.[11] In this testimony and in a later journal article,[12] Pedatzur reported that the Israeli studies find little or no evidence of Patriot success—*at most one* or *two* warhead kills. A year and a half later in 1993, Moshe Arens, former Israeli Minister of Defense, and General Dan Shomron, Chief of Staff of the Israeli Defense Force during the war, stated in interviews conducted by Pedatzur on Israeli television[13] that the Patriot successfully intercepted at most one Scud over Israel. Later, on a PBS "Frontline" program in January 1996 Arens repeated similar statements about the findings of the Israeli studies.[14] It is now clear there were intense disagreements between Israeli military and government officials and their U.S. counterparts over Patriot performance during the war.[15]

The panel focused on the Army studies and the commercial video study. We discuss each in detail later in this article. The panel chose not to look at the two studies of casualties and building damage in Israel because the analysis based on the video data seemed more comprehensive and because it had become the most controversial element of the Patriot debate. For completeness, however, we next briefly describe the two studies of casualties and ground damage in Israel. Historically, the first of these was the catalyst of the public debate over Patriot performance.

CASUALTIES AND STRUCTURAL DAMAGE IN ISRAEL

On the basis of unclassified casualty and structural damage data reported by Israeli media, Theodore Postol, a physicist and professor of science and technology policy at MIT, published an article in the winter 1991/92 issue of *International Security*[16] in which he argued that the success of the Patriot must have been significantly lower than official reports. In particular, he concluded that ground damage in Israel was greater after the introduction of the Patriot than before and while this difference was not statistically significant, it was inconsistent with the Army's then claim of a 96% Patriot success rate. While much of his article was directed to claims of linkage to the Strategic Defense Initiative asserted by others, Postol's conclusions about Patriot performance ignited a storm of protest. Robert Stein, a systems engineer at Raytheon Company, published a rebuttal in a subsequent issue of the journal[17], which was accompanied by a response from Postol. There were other criticisms of the Postol conclusions as well.[18] Later, a more detailed study[19] of damage data in Israel was carried out by a group of three physicists: Steve Fetter (University of Maryland), George Lewis (MIT), and Lisbeth Gronlund (Union of Concerned Scientists and MIT), with results that supported the findings of the earlier Postol study.

OFFICIAL ARMY STUDIES

The two Army studies of Patriot performance are closely related because they use similar databases and because they were performed by the same organizations. Officially, the first study was withdrawn when the second was released, but it is nevertheless useful to discuss it because unclassified reviews of the first study give considerable insight into the character and quality of data used by the Army in both of its studies. Before proceeding further, it is useful to recall the distinction between intercept attempt and engagement. The former refers to the interplay between a single Patriot interceptor and Scud whereas engagement refers to the set of all intercept attempts against a given Scud.

Ground Impact/Patriot Unit Database

As mentioned earlier, the lack of recording devices on Patriot ground control units means that records of radar "track files," system status, and other related information were not routinely collected during the Gulf War. The only manner in which operators in standard Patriot control units in Israel or Saudi Arabia could preserve technical engagement information was to manually request printouts of certain kinds of track and system functionality data by pushing a control panel button. This was not routinely done and, even when it happened, the result was far from a continuous record. In a few cases in Saudi Arabia and Israel, video cameras were placed inside Patriot ground control units to record what was displayed on control panels and screens. The totality of the technical data collected from Patriot ground control units during the war along with operator and unit status reports constitutes the first part of the database used by the Army.

The second part of the Army database consists of ground impact data, coming primarily from inspection of impact craters and Scud missile debris found in or near these craters. Collection of ground impact data in Saudi Arabia during the war was the responsibility of local Army units under the direction of and in coordination with the Saudis. These collections were not done on a systematic basis. Limited investigations of about one-third of the Saudi engagements were made in Saudi Arabia by a single engineer from the Army Ballistic Research Laboratory, days and weeks after the impacts occurred, when craters had often been filled in and any missile debris removed.[20] The ground damage database available to officials in Israel is reported to be considerably more complete than is the case for Saudi Arabia because the Israelis did rapid follow-up and systematic collections after each Scud attack—a task no doubt aided by the predominantly urban environment of the Tel Aviv area. (We do not know whether the Israeli data were used in the Army studies.) Reviews done by analysts at GAO[21] and CRS[22] report that the ground impact data used by the Army are far from comprehensive and are difficult to interpret in many cases. In what follows, we refer to the totality of ground impact damage data and technical engagement data of all types collected from Patriot units during the war as the ground impact/Patriot unit database.

Two Army Studies

The Army's first analysis of Patriot performance was completed in May 1991, and the results were released publicly in December of that year: a success rate of "over 80% in Saudi Arabia and over 50% in Israel."[23] This classified study was later reviewed in detail by GAO and CRS analysts. Representatives from these organizations testified about their findings at the 1992 HGOC hearings.[21, 22] The GAO and CRS reviewers concentrated on the study methodology and the data used by the Army but did not attempt to reanalyze the ground impact/Patriot unit database. Both of the Congressional reviews identified serious problems with the first Army study. There can be little doubt that the criticisms made in these reviews were influential in the Army's decision to undertake a second study.

The second Army study, which began in February 1992, used an alternative methodology and a modified database obtained by discarding certain records identified by GAO and CRS as completely unsuitable for analysis. The results of the new study were first presented publicly by the Army at the April 1992 HGOC hearings.[23] The Patriot success rate was reported as "over 40% for the engagements in Israel and over 70% for the engagements in Saudi Arabia."[24] The success rates do not include uncertainty estimates, and it is unclear what if anything the term "over" is intended to convey in the reported success rates. The reported success rates imply about 6 Scuds successfully intercepted over Israel and about 20 Scuds successfully intercepted over Saudi Arabia, using the engagable Scud totals presented in the introduction. These findings of the second Army study stand today as the official position of the Army and Pentagon for the wartime success of the Patriot system. The Army study reports, database, and the engagement scores on Scud-by-Scud basis remain classified.

The Army methodology of the second study scored an engagement as a success if (1) an engagable Scud was present, and (2) at least one Patriot interceptor was guided to the vicinity of an intercept point, and (3) absence of evidence of significant ground damage. If only condition (1) was satisfied and either one or both of conditions (2) and (3) were not, the engagement was scored a failure. Successful engagements were partitioned into four categories: the incoming Scud warhead was either (a) destroyed, (b) dudded, (c) had its yield reduced to "low value," or (d) the warhead was deflected outside the defended area. Cases (a) or (b) are defined by the Army as "warhead kill;" cases (c) and (d) as "mission kill."

The second Army study reports a total of four mission kills: two deflections and two reductions to "low" yield among all 44 of the engagable Scuds.[25] The magnitudes of the deflections scored as mission kills in two engagements are not publicly reported, nor is it known how the Army determined these deflections from available data. Because the collision of one or a few 50-g Patriot warhead fragments with a rapidly moving Scud warhead would give an insignificant deflection from momentum conservation considerations alone, a meaningful deflection could result only if the collision altered the aerodynamic characteristics of the Scud warhead section or the blast effects of a Patriot explosion caused the deflection. Finally, it seems certain that the complex trajectories followed by the Scud warhead sections following breakup must have degraded the impact point prediction accuracy of the Patriot system.

It is also not known publicly what is the nature and quality of the data supporting the Army's finding that the Patriot was the cause of the reduction to low yield of the two other engagements scored as the mission kills.

To give a measure of the quality of the data used to score each event, Army analysts partitioned their data into three categories: high-, medium-, and low-confidence. In scoring engagements, the Army analysts used certain normative rules when combining data with differing confidence levels. The performance of the Patriot system against every engagable Scud was scored in the second Army study, whatever the quality of the available data. Two engagement outcomes were scored "unknown."

Subsequent to the HGOC hearings, GAO published in September 1992 a review of the Army's second study;[26] no counterpart CRS report exists. This latter GAO review concentrates on those engagements for which the Army reported high confidence of destruction or disablement of Scud warheads; these cases represent 25% (about 11) of all engagable Scuds. The GAO review makes a number of salient points. It quotes the Deputy Project Manager for Patriot as stating that "the assignment of a high-confidence level to an engagement's outcome did not mean that the Army was absolutely confident that the assessed outcome was correct. Rather, given the limited data available for assessment purposes, the Army scorers have higher confidence in the assessed outcome of those engagements than in others." The partition of warhead kill scores in the second Army study between the medium- and low-confidence categories is not publicly available.

The GAO report states that only about 4 of the 11 Scuds rated by the Army as high confidence warhead kills are supported by "strong" evidence.[27] Examples cited by GAO of what the Army considered strong evidence of a warhead kill include: recovery of a Scud warhead section containing Patriot fragments; or holes in a recovered warhead or in the guidance or fusing components; or radar data showing evidence of Scud debris in the air following a Patriot detonation. It is not clear from the public record if actual Patriot fragments were found in recovered Scud warheads.

The GAO report indicates that the other 7 Scuds scored by the Army as high confidence warhead kills are not supported by "strongest" evidence. While for some of these latter engagements, radar-tracking data exists that proves a Patriot interceptor came close to a Scud, the GAO report emphasizes that computer data collected from Patriot units cannot be used alone to prove that a Patriot destroyed a Scud warhead. One source of confusion during Gulf War operations was that a "fusing symbol" appeared on the Patriot operator's panel when signals received by the ground unit from a Patriot interceptor cut off at the expected time of fusing (Patriot warhead detonation). However, the appearance of this symbol alone did not indicate proximity to the target nor that the Scud warhead section was visible to the fusing radar of the Patriot interceptor. In this connection, the GAO report quotes, "The Chief Engineer [of the Patriot Program Office] said that the Patriot's fuse can sense its target and detonate at up to six times the required miss distance, resulting in an extremely low or no probability of kill. However, the system would still record a kill."

The GAO report also states that ground damage searches in Saudi Arabia were insufficiently complete to indicate how many warheads overall the Patriot killed. Clearly, this situation could have caused an upward bias in the reported Patriot success rate because the Army study used absence of evidence of ground damage as evidence for Patriot success.

POSTOL-LEWIS ANALYSIS OF COMMERCIAL VIDEOS

Commercial Video Database

In early 1992, Theodore Postol and George Lewis concluded that the commercial videos could be used to draw conclusions about the success of Patriot-Scud engagements and intercept attempts. (We will refer to these records as the "commercial videos.") The conclusions drawn by Postol and Lewis were vigorously challenged when presented publicly.[28] Since then Postol and Lewis have progressively augmented and strengthened their analysis in response to their critics. The most complete report of the Postol and Lewis methodology thus far published is contained in their 1993 *Science and Global Security* article.[29] Subsequent to that publication, Postol and Lewis have carried out further analyses of Scud-Patriot video data from the Gulf War and expanded the scope of their findings.[30]

Our review first concentrates on the engagements described in the 1993 article and the criticisms of that analysis, and then we discuss the subsequent analysis of Postol and Lewis of additional engagements. The technical issues involved in the two phases of the Postol-Lewis work are essentially the same. The differences correspond primarily to the completeness of the video data and certain details of their scoring procedures for the more recent work.

In carrying out their analysis, Postol and Lewis assembled as complete a set of commercial videotapes as feasible. Wherever possible, copies of unedited (uncut) tapes were used. With the exception of a video presented on U.S. television that shows imagery taken by an infrared camera (most likely in Israel), all of the imagery used in the analysis was taken using conventional (visible spectrum) video cameras that were typically hand-held and hand-slewed. The precise camera locations and ranges to the engagements being photographed are unknown, and the brands, focal lengths, and settings of the cameras were generally unknown as well. In many cases, Postol and Lewis were able to exploit objects in the foreground and other clues in the imagery to determine camera locations—often the rooftops of hotels where reporters were staying. By means of a variety of clues, Postol and Lewis determined that their collection of videos contained numerous cases of duplicate imagery of engagements recorded by two or more cameras at different locations. For all but three videos, they were able to determine definitely the presence or absence of duplicate imagery. (Only two of these three are part of the discussion that follows.)

For convenience of discussion, we divide the totality of engagements scored by Postol and Lewis into two classes. Class A consists of engagements for which the most complete video data exists: 29-32 intercept attempts on 15–17 Scud missiles,[31] that is 34%–39% of all engagements during the war. Videos in this class show Patriot fireballs and Scuds jointly in a sequence of frames. For Class A events, Postol and Lewis score individual intercept attempts on each Scud and net engagement outcomes. The breakdown of engagements by location is: Tel Aviv, 4 engaged; Riyadh, 8; Dhahran, 4; and Unknown, 1. Except for the latter engagement, the dates of all engagements are known. The analysis and results for these engagements are presented in the Postol-Lewis *Science and Global Security* article, with the analysis of three Scud engagements presented in full detail.[32,33] Table A, "Postol-Lewis Engagement Scores: Video Available of Intercept Attempts," lists all the Class A engagements together with related information to be explained later.[34]

Class B engagements of the Postol-Lewis video analysis consists of another 12 Scuds for which the video data are less complete. These latter videos do not show Patriot fireballs and Scuds jointly and thus Postol and Lewis are able to report only overall engagement scores. Table B, "Postol-Lewis

Engagement Scores: Video Not Available of Intercept Attempts," lists all Class B engagements together with related information.[35] Taking Classes A and B together, Postol and Lewis score 27–29 (61%–66%) of all 44 engagable Scuds.[36]

Video Analysis Methodology

We begin with a summary of the Postol-Lewis methodology for Class A events, emphasizing the key points.

The Scud velocity vector and the direction of gravity (a vector toward the earth's center) define the trajectory plane. Aside from spiraling (helical) motions of the Scud warhead induced by asymmetric drag or by an out-of-plane impulse introduced during an intercept attempt, the trajectory plane is fixed in space. The breakup of incoming Scuds results in multiple objects, a long stream of debris, and large wakes. Postol and Lewis argue that the leading, visible object coming out of the debris cloud is the (non tumbling) Scud warhead section. They further argue that the low drag of the warhead section ensures it will have the highest velocity of all the falling objects that result from a Scud breakup.

In analyzing video imagery of intercept attempts, Postol and Lewis use the *video jump distance (JDV)*, the apparent distance the Scud (or Scud warhead) moves between successive video frames as a spatial metric, but they do not convert this metric to an actual distance in meters, except for purposes of illustration or for order-of-magnitude estimation. The video jump distance is central to their scoring of intercept attempts. In practice the video jump distances were measured by Postol and Lewis with a millimeter ruler directly off freeze-frame images on a large video monitor. The exposure (shutter) times for the video imagery are not known. Commercial video cameras can come with automatic shutter speeds that vary with illumination conditions, or with manually set shutter speeds, or both. Whatever the situation was for the cameras used to take the Gulf War news videos, the lack of streaking indicates that the Scud image did not move many pixels during the time it took to capture an image and thus shutter speed (as opposed to framing rate) is not a critical issue.

If the video camera was not viewing the Scud motion at right angles, the video jump distance is *smaller* than the *true jump distance (JDT)* according to $JDV = JDT \sin\alpha$ where α is the angle between the camera bore sight axis and the Scud velocity vector. To get a feel for the actual jump distance, consider an intercept altitude of 10–12 km at which the Scud velocity is characteristically 2.0 km/s. Then for orthogonal viewing $JDV = JDT = 70$ m, given a video camera framing rate of 1/30 second. At much lower altitude, say 3 km, the jump distance for orthogonal viewing is approximately 33 m due to a decrease of the warhead velocity caused by atmospheric drag. As the angle α approaches zero, the video jump distance shrinks to zero, but this did not occur in any of the Gulf War videos. If it had occurred, the signature would have been unmistakable. *The key point: the video jump distance sets the scale of the spatial resolution achievable using the video data.*

A Patriot interceptor missile becomes invisible at nighttime after burnout (except in imagery taken within the infrared), but its position at the time of warhead detonation is clearly indicated in the videos by a bright region, unless clouds intervene. The resulting Patriot "video fireball"[37] persists for multiple (10–15) video frames and is essentially *fixed* in space because the hot expanding gases are quickly slowed by the atmosphere. The video fireball provides a reference point that Postol and Lewis use to correct for camera motion.

The apparent sizes of the Patriot video fireballs seen in the videos (transverse dimensions range from 50–400 m) are far larger than the Patriot interceptor lethality distance (5-10 m), which has been established under controlled conditions. A simple fireball model using standard phenomenology predicts a fireball radius of the order of magnitude of the kill distance for the Patriot interceptor. A daytime photo from a Patriot test similarly shows a fireball radius far smaller that is seen in the Gulf War imagery.[38] In addition to having surprisingly large sizes, the Gulf War Patriot video fireballs are often non circular. No unique explanation has been established for the difference between the video and the actual (true) Patriot fireball sizes. Possibilities range from atmospheric effects, internal scattering within the camera optical system, focal plane saturation, or a combination of such effects.

The actual dimensions of the video fireballs play no significant role in the Postol-Lewis analysis *provided the video fireball radii are large* compared to the Patriot kill distance. Under such conditions, the asphericity of the video fireballs and the location of the Patriot interceptor fragment pattern within the fireball are unimportant. This will become clearer shortly.

Postol and Lewis assign each Patriot intercept attempt to one of two categories: (i) fireball overlap (potential kill), and (ii) clear miss. They do so by the following procedure: First, they look at a number of successive frames after the Patriot video fireball first appears, to get a good estimate of the jump distance for that event, taking out the camera motion as described earlier. Then they go back to the frame in which the Patriot fireball first appears, which we refer to as frame 1. If the Scud warhead is covered by the Patriot fireball in frame 1, the event is classified as a "fireball overlap." For these events, *Postol and Lewis make no estimate of the miss distance.*

For all other events, Postol and Lewis introduce an apparent "miss distance" by drawing a straight line in frame 1 from the Scud warhead section to the centroid of the video fireball, and they measure the length of this line in units of the video jump distance. We will refer to the length of this line as the Postol-Lewis miss distance *(MDPL)*. What relationship does the *MDPL* have to the true three-dimensional miss distance? To answer this question, consider the intercept attempt as viewed in three-dimensions. The case in which the Patriot fireball intersects the Scud trajectory in front of the Scud position in frame 1 is illustrated in Figure 3(a). (In viewing Figs. 3(a), 3(b), and 3(c) note that for convenience of presentation the sizes of the Patriot fireballs are drawn subscale. In the scale used for the jump distances, the video fireballs would appear larger by as much as a factor of ten.)

Two factors need to be taken into account to understand the utility of the Postol-Lewis miss distance: (1) The camera viewing angle, and (2) the distance the Scud travels between the (unknown) time the Patriot interceptor fused and the time camera shutter opened to take frame 1.

First we define the "true Postol-Lewis miss distance" *(MDPLT)* as the length of a three-dimensional vector drawn from the centroid of the Patriot fireball to the position of the Scud in frame 1. Because of the approximately co-linear (head-on) geometry of Patriot-Scud encounters, the *MDPL* vector will be oriented approximately parallel to the Scud trajectory when the interceptor is flying up the anti-trajectory as illustrated in the figure. The projection of the *MDPL* vector onto the plane perpendicular to the camera bore sight axis is the Postol-Lewis miss distance. Hence, $MDPL = MDPLT \sin\alpha$ as shown in the insert of Figure 3(a). Now consider the effect of Scud motion between adjacent frames.

In the geometry illustrated in Fig 3(a), the Patriot fireball appears in *front* of the Scud position in frame 1 (solid square in the figure). The *true miss distance (MDT)* is the length of a line drawn from the centroid of the Patriot fireball to the position of the Scud warhead, indicated by X in the figure, at the instant the Patriot interceptor fused (which must have occurred between frame 0 and 1). The distance $xJDT$ shown in the figure is the distance the Scud traveled between the time of Patriot fusing and the time the video camera captured frame 1. The value of the parameter x cannot be obtained from the videos because one has no way of determining when the Patriot fused in the interval between the times frames 0 and 1 were captured. However, it must be true that $0 \le x \le 1$. From Figure 3(a) we can write,

$$MDT = MDPLT + xJDT = JDT(N + x) \quad (1)$$

where in the last step $N = MDPLT / JDT$ has been used to measure the true miss distance in terms of the true jump distance *JDT*. The measure N need not be an integer. We can re-express the right hand side of Eqn. (1) in terms of the observable video jump distance and use the fact that $\sin\alpha \leq 1$ to obtain a useful lower bound on the true miss distance.

$$MDT = JDT(N+x) = \frac{JDV}{\sin\alpha}(N+x) \geq \frac{JDV}{\sin\alpha}(N) \geq JDV(N) \qquad (2)$$

If the product *JDV(N)* greatly exceeds the Patriot kill distance, the Scud warhead could not have been killed.

In the case illustrated in Fig 3(b), the fireball intersects the Scud trajectory *behind* the Scud in frame 1 but in front of the Scud at the time of fusing. This is the geometry required for warhead kill, provided the Patriot fireball is located at a point slightly in front of the Scud at the time of Patriot fusing.[39] For this geometry we can write,

$$|MDT| = |MDPLT - xJDT| = JDT|N-x| \qquad (3)$$

where N is again the measure *MDPLT / JDT*. In Eqn. (3) we have inserted absolute value signs to avoid the complication of dealing with negative miss distances. A useful lower bound for the magnitude of the true miss distance again follows.

$$|MDT| = JDT|N-x| = \frac{JDV}{\sin\alpha}|N-x| \geq \frac{JDV}{\sin\alpha}|N-1| \geq JDV|N-1| \qquad (4)$$

Clearly the right-most side of Eqn. (4) gives a valid bound for the magnitude of the true miss distance for both Figure 3(a) and 3(b). We see that if the product $JDV|N-1|$ greatly exceeds the Patriot kill distance, a non-kill is ensured for either of the geometries considered.

The cases illustrated in Figs. 3(a) and 3(b) represent true miss distances that are small when measured in terms of the true jump distance. Figure 3(c) shows how Figure 3(b) would look for a much larger miss distance, a not uncommon occurrence. Eqn. (4) applies also to this situation. Generally, any event in which the Patriot fireball occurs behind the Scud position in frame 0, must be a miss.

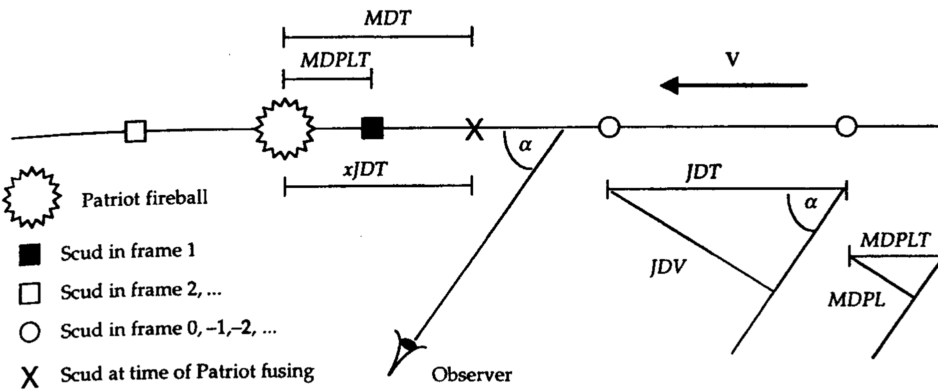

Figure 3 (a): An example of a Patriot intercept attempt where the Patriot fireball intercepts the Scud trajectory and is located in front of the Scud in frame 1, the first video frame in which the fireball appears. Fusing must have occurred somewhere between frames 1 and 0. (In scale, the fireball would appear about 10 times larger than drawn, thus for a fireball overlap, the Scud would be covered for several frames.) The observer is a video camera whose bore sight axis makes an angle α with respect to the Scud trajectory in space, which may be assumed to be a straight line over the time interval of interest. The true miss distance (*MDT*) and the true Postal-Lewis miss distance (*MDPLT*) are shown above the Scud trajectory. The difference between these distances, due to motion of the Scud between the times at which frames 0 and 1 were captured, can be expressed as a fraction *x* of the true jump distance as shown below the Scud trajectory. The parameter *x* cannot be determined from the video data, but must lie between 0 and 1. The large and small triangular inserts show, respectively, the jump distance as seen by the video observer (*JDV*) and the Postol-Lewis miss distance (*MDPL*) meaureable on the videos. Postol and Lewis use the ratio of *MDPL* to *JDV* to sort intercept attempts into clear misses and fireball overlap categories according to criteria described in the text.

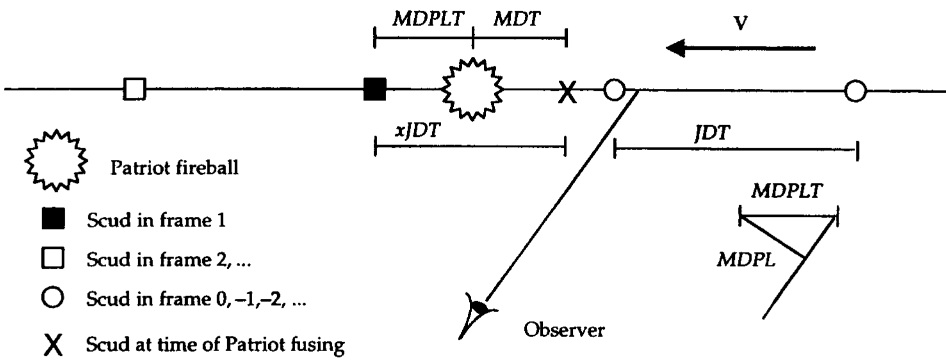

Figure 3 (b): An example of a Patriot intercept attempt where the Patriot fireball intercepts the Scud trajectory and is located behind the Scud in frame 1, but in front of the position of the Scud (point X in the figure) at the time the interceptor warhead detonates. This special case of this geometery where the point X lies withinh the fireball is a necessary, but not sufficient, requirement for Scud Warhead kill.

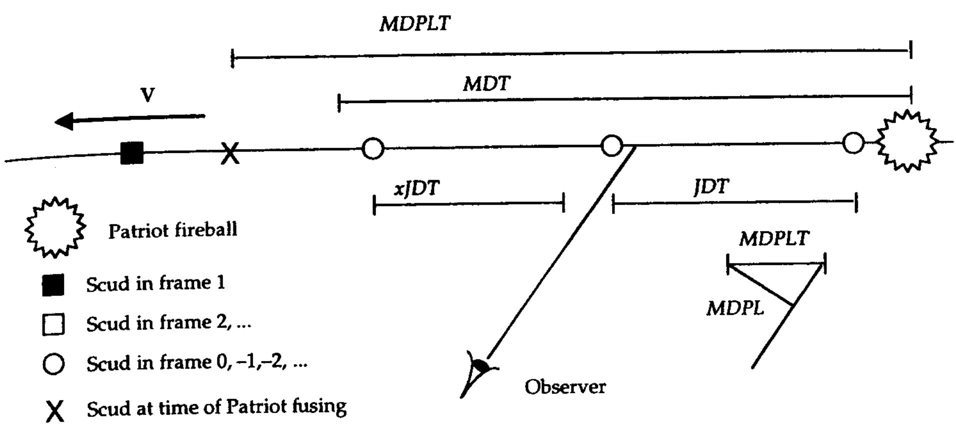

Figure 3 (c): Patriot intercept attempt where the Patriot fireball intercepts the Scud trajectory and is located several jump distances behind the position of the Scud in frame 1 and thus necessarily well behind the position of the Scud at the time of fusing. This geometry, which appears frequently in the videos, is an unambiguous clear miss.

The validity of the analysis described above does not require that the centroid of the Patriot interceptor warhead fragment pattern coincide with the centroid of the Patriot fireball. Given the large size of the video fireballs, the only assumption required is that the interceptor warhead fragment pattern be located somewhere inside the fireball.

What if the Patriot fireball does not intersect the Scud trajectory? This is the easiest case of all. Any such intercept attempt must be a miss, with no calculations required. If the Patriot fireball intersects the Scud trajectory in three dimensions, it will appear to do so in any two-dimensional image *what-*

ever the angle of viewing. The converse is not true. It may happen that the Patriot fireball appears to intersect the Scud trajectory when viewed from a particular vantage point, but the fireball is actually offset from the trajectory in three dimensions along a line from the camera to the Scud trajectory. In such cases, the value of the Postol-Lewis miss distance may not have any particular significance, but its use will not cause a potential kill to be incorrectly classified as a clear miss.

In the limit the viewing angle α goes to zero, the bound given by the right most factor in Eqn. (4) remains true but becomes useless because $JDV \rightarrow 0$ in this limit. For small α it is better to use the bound given by the next-to-right most factor in Eqn. (4), although this requires knowledge of the angle. When an estimate can be made of the location of the impact point with respect to the camera location, a value for $\sin\alpha$ can be estimated from the video imagery given that the reentry angle and reentry velocity of the Scud are fairly well known—the Scud trajectory is not an arbitrary curve in space. However, as the angle α becomes very small, the uncertainties in this process grow. Even in the extreme of very small α where one is viewing the trajectory essentially end on (video jump distance very small), there is no difficulty in distinguishing fireball overlaps from clear misses. All that is needed is to look at the videos to determine the presence or absence of a fireball overlap; no measurements are required.

We summarize. It is correct to say that the true miss distance cannot be determined from video data alone. There are two reasons why this is so: (1) video camera captures the location of objects only every 0.033 s, and (2) the video image only provides a two-dimensional image of an intrinsically three-dimensional event.[40] Postol and Lewis are, nevertheless, able to draw conclusions about the miss distances of a large number of intercept attempts using the videos. *The basic reason is simple: if the apparent miss distance is large enough, the video data provides unambiguous evidence of a miss.*

In particular, Postol and Lewis classify an intercept attempt as a "clear miss" and conclude that the Patriot could not have caused damage to the Scud warhead only if the *MDPL* is three or more times the video jump distance, $N \geq 3$ in the notation of Eqn. (4). There is nothing special about this particular choice of cutoff. They use it as a matter of simplicity because there are no events with smaller video miss distances all the way down to fireball overlap events for which Postol and Lewis make no estimates of a miss distance. That is, the *MDPL* distribution is bimodal—*every clear miss has a* MDPL *large compared to the corresponding video jump distance.*[41] The above choice of cutoff is also conservative in the sense that it further removes concerns about what region within the fireball corresponds to the lethality zone of the Patriot

[redacted] [redacted]

warhead fragments.

Scoring the Class A Scuds

Table A lists by date and place the video and other related information used for scoring 15-17 Class A Scuds, for which there are data pertaining to a total of 29-32 intercept attempts. The distribution is as follows: 6 Scuds, 1 intercept attempt each; 8 Scuds, 2 intercept attempts each; 2 Scuds, 3 intercept attempts each; and 1 Scud, 4 intercept attempts. Table A is an expanded version of information given in the Postol and Lewis *Science and Global Security* article coming from their subsequent work.[34] We constructed this table to facilitate understanding of the precise details used by Postol and Lewis to score engagements, a step that the reaches beyond scoring intercepts attempts that is the primary focus of their *Science and Global Security* paper. Note, however, that the engagement score typology listed in the table (F1–F8) are the authors' creation to provide a shorthand for the reasoning and data behind the failure scores assigned by Postol and Lewis.

For the 32 intercept attempts on the Class A Scuds, Postol and Lewis score 24 as clear misses and 8 as fireball overlaps by means of the methodology described earlier. One Scud has two fireball overlaps; six other Scuds have one fireball overlap each.

The 10 Class A engagements that show only clear miss intercept attempts are scored by Postol and Lewis as failures. This step in the analysis is the *only point* at which Postal-Lewis make use of a miss distance. The basic argument has already been discussed; it is physically impossible that Patriot warhead fragments could ever have reached any part of the Scud warhead section. The columns in the right half of the table indicate that in many of these engagements, Postol and Lewis are able to cite additional information supporting a failure score. For four Scuds (A1, A3, A7, and A9), they cite evidence of extensive ground damage; we designate these scores by F1. Six Scuds (A1, A3, A7, A9, A15, and A16) were tracked all the way to the ground and shortly thereafter, a large, bright flash is seen that persists for 1–2 seconds. Postol and Lewis interpret these flashes as detonations of live Scud warheads; we designate the scores by F2. Four Scuds (A2, A10, A12, and A13) were not tracked all the way to the ground and hence there is no information concerning ground flashes, nor is there evidence of extensive ground damage available; we denote these scores by F3.

For the 7 Scuds with fireball overlaps, Postol and Lewis call upon additional information to ascertain kill or no-kill of the Scud warhead. For three of these Scuds (A6, A8, and A11) a high-beta (low-drag) object emerges from the fireball and is tracked all the way to the ground and a ground flash is observed. (For Scud A11 there is a cut in the video tape between the second intercept attempt and the ground flash, but the evidence of extensive ground damage provides corroborative evidence for a failure score, which we denote as F4.) As for the clear-miss Scuds scored as F2, Postol and Lewis interpret these ground flashes as the detonation of live Scud warheads, and thus score these three engagements as failures; we designate the scores by F5. For two of these engagements (Scuds A6 and A11) Postol and Lewis report that the videos show evidence of a "hit" by Patriot. To wit, the appearance of the Scud warhead section after the fireball overlap is visibly different and significantly brighter following the fireball overlap, consistent with an increase in the amount of debris streaming from the Scud warhead section. Given that Scud A11 is the one engagement that has two fireball overlaps, there are only four Scuds in Table A that remain to be discussed.

Scud A5 is not tracked in the video all the way to the ground and thus no evidence is available concerning a ground flash. There is also no evidence for or against extensive ground damage. For Scud A14, the story is similar except that Postol and Lewis are uncertain whether or not the Scud was tracked all the way to the ground. The video ends at about the time they would expect a ground flash. Postol and Lewis score these two engagements as failures citing lack of video evidence of a "hit" and also the emergence of a high-beta object from the fireball overlap on a trajectory essentially unchanged from that prior to the Patriot fireball. We designate these scores by F6.

Scud A4 shows evidence of a Patriot "hit," i.e., a significant change in appearance after the fireball overlap. Postol and Lewis are uncertain whether this Scud was tracked all the way to the ground, but in any case no ground flash is observed in the videos. The Scud warhead was recovered and hence was a dud (consistent with there being no ground flash assuming the camera was looking). The event is one of three duds reported by the Army to have landed during the war *after* deployment of Patriot.[42] Postol and Lewis challenge the Army's assertion that Patriot caused the dudding, on the grounds that it is unlikely that Patriot warhead fragments could have reached the fusing mechanism located behind the warhead without passing through and driving to detonation the high explosive in the Scud.[43] We designate this Postol and Lewis score as F7.

Scud A17 is the last of the four "hits" listed in Table A. The warhead was not tracked all the way to the ground and there is no evidence one way or the other concerning a ground flash or extensive ground damage. Postol and Lewis score the engagement as a failure because they see no evidence in the videos that the Scud warhead broke up following the fireball overlap. In particular, after the intercept attempt, they see a high-beta object emerging from the fireball on an essentially unchanged trajectory. We denote this score as F8.

Clearly, the validity of the Postol-Lewis scores F3, F6, and F8 depend on the quality of their evidence that there were no other unseen Patriot interceptors that could have made a successful intercept. Note, however, for any engagement for which the Scud was picked up at high altitude and tracked all the way to the ground, the videos alone provide evidence that no other Patriot detonations occurred anywhere near the Scud trajectory.

Scoring the Class B Scuds

Table B lists details of the 12 Class B engagements and the data used by Postol and Lewis for scoring. As for the previous table, the organization and engagement score typology of Table B is that of the authors. The methodology used by Postol and Lewis to score these engagements is basically the same as that used in scoring the fireball overlap Scuds of Class A. In one case (B10) an extra argument is needed.

Scuds B1 and B11 are not tracked to the ground (B1 is not seen at all), but they are scored as failures by Postol and Lewis on the basis of extensive ground damage. We denote these scores by F9.

For eight of the Scuds (B2, B3, B4, B6, B7, B8, B9, and B12) the engagements are scored as failures by Postol and Lewis on the basis of an observed ground flash; we designate these scores by F10. For two of these Scuds (B4 and B7), the Scud warhead is not seen on the videos. For Scud B12 both ground flash and extensive ground damage evidence are available and so it has a dual score F9 and F10. This score cannot be contested; it is the Scud that destroyed the Dhahran barracks.

Scud B10 is a special case. It is visible in the videos, but only initially. Evidence is not available concerning a ground flash or extensive ground damage. Postol and Lewis score the engagement as a failure by arguing that the two Patriots seen in the videos were launched too late to have gotten within interception range of the Scud before impact. We denote the score by F11. The validity of this score depends on the quality of the evidence Postol and Lewis have that the two visible Patriot interceptors were launched too late and that no other interceptor was ever in position to make a successful intercept.

Scud B5 shows a ground flash and would also be scored a failure (F10 in our notation) except Postol and Lewis are not certain it impacted within the Patriot footprint (i.e., the defendable area), and so they score the engagement as a *possible* failure, a score we denote as O1 (other).

Summary of the Postol-Lewis Scores

For the 29 engagements that Postol and Lewis score on the basis of video data, supplemented in several cases by extra-video evidence, they find: (1) lack of evidence for even a single Patriot warhead kill; (2) evidence for 28 engagement failures; and (3) one engagement which cannot be scored conclusively because it may have been outside the defended perimeter. (If the Scud was inside the defended area, the Patriot score would be failure.) Postol and Lewis are certain that at least 27 of these 29 engagements are distinct, and believe that at least 28 are distinct. Using 44 as the total number of engagable Scuds in the Gulf War, 27-29 represents a population sample of 61%–66%. In addition to the 29 engagements they score, Postol and Lewis have video data on three other engagements, but they judge the evidence contained therein insufficient for scoring.

CHALLENGES TO THE VIDEO DATABASE AND ANALYSIS

The methodology and conclusions of Postol and Lewis have been repeatedly challenged, but it does not appear that any of their critics—with one exception—has ever attempted to analyze the video data using the Postol-Lewis methodology, or any other methodology. We first discuss the general nature of the challenges to the use of commercial video data, and then we discuss specific technical criticisms of the Postol-Lewis analysis.

The Army and Raytheon reportedly used some commercial videos of Scud engagements to aid in understanding the complex motions of the Scud warhead before and after missile breakup. The Army did not, however, use any of the videos to determine the outcome of Scud engagements in either of its two studies discussed earlier. The official position of the Army is that the commercial videos cannot be used for this purpose. Raytheon's position is identical. The Army's position corresponds to the findings of an unclassified study it commissioned to evaluate the utility of the commercial video database. That study,[44] which we have reviewed, was done by the Material Test and Evaluation Directorate of the U. S. Army White Sands Missile Range (WSMR) and issued shortly before the HGOC hearings. The regular work of the directorate includes the recording and interpretation of data from missile test firings, typically using multiple phenomenologies (radar, infrared, and visible). Video imagery of tests at WSMR is taken using multiple high-speed tracking cameras at different locations, typically under daylight conditions.

The WSMR report on the utility of the commercial video database is cursory at best. After accurately stating a number of limitations of data obtained from commercial videotapes, which in fact are fully taken into account by the Postol-Lewis methodology, the report concludes that no useful information about Patriot performance could be gained from analyzing such data.

Following the HGOC hearings, then Chairman John Conyers requested that Postol and Lewis conduct a review of the WSMR report.[45] In their review, Postol and Lewis pointed out that almost all of the video used by WSMR in its studies was derived from newscasts, which are nearly always edited (cut and spliced) to meet programming constraints. By confining its review to secondary sources, the WSMR review team missed much valuable information present in the raw, unedited primary sources. Postol and Lewis also pointed out numerous other shortcomings of the WSMR review. The MIT review also contains useful compilations of miss distance data obtained by Postol and Lewis from their analysis of their video tape collection.

Peter Zimmerman, a physicist then at the Center for Strategic and International Studies in Washington, DC, argued in testimony presented at the HGOC hearings[46] that *almost always* the first frame containing a Patriot fireball would show the fireball well behind the Scud warhead if Patriot fusing occurred slightly in front of the Scud warhead—as required for a warhead kill—because of the slow framing rate (30 per second) of commercial video cameras. As a result, he argued, warhead kills would frequently be incorrectly classified as "clear misses" using the MIT methodology. Zimmerman also challenged the Postol-Lewis interpretation of ground flashes as definitive evidence of Scud warhead explosions (detonations). He suggested instead that the ground impact flashes could be "kinetic energy flashes" generated by the high-speed impact of a dudded Scud warhead or a missile body fragment; the burning of residual Scud fuel; or the deflagration (turbulent burning but not detonation) of a Scud warhead. Overall, he argued that videotapes could not be used to draw useful conclusions about Patriot performance.

Subsequent to the HGOC hearings and in response to a request from then Chairman John Conyers following those hearings, Zimmerman conducted a review of the WSMR report as well.[47] Generally he agreed with the overall conclusions of the WSMR report on the disutility of using the video data to access Patriot performance, but he was critical of some aspects of the WSMR report. Going beyond a mere review, Zimmerman also attempted an analysis of the video data using the video fireball diameter as a spatial metric. He estimated the actual fireball diameter to be about 8.8 m at 11 km altitude and assumed the video fireball diameter coincided with that dimension. Using this metric, he argued that the Postol-Lewis miss distance would have to exceed *at least ten* video fireball diameters (about 88 m by his spatial metric) before an intercept attempt could confidently be classified as a "clear miss."

Later at the May 1993 Washington meeting organized by the ad hoc panel, Zimmerman stated that he no longer supported this analysis and accepted that video fireball diameters greatly exceed 8.8 m. At the same meeting, Zimmerman continued to argue that the correct interpretation of the majority of the ground flashes need not signal a warhead *detonation*, citing as evidence flashes present in videos taken of high-velocity collisions in tests of the Line of Sight Anti-Tank (LOSAT) missile at White Sands. (This missile has an armor-penetrating, non explosive warhead.) Lastly, he raised a new concern about the Postol-Lewis methodology at the meeting. Zimmerman argued that the leading visible object in the commercial videos need not include the Scud warhead, but instead might be a portion of the Scud body. However, he presented no detailed analysis to support this new hypothesis.

Neither the GAO nor the CRS has ever analyzed the Gulf War video database or *independently* evaluated its utility for scoring Patriot-Scud intercept attempts or engagements. There does exist, however, one GAO report [48] that discusses the videos, but it provides no technical information. The GAO report merely quotes the WSMR report cited above and a variety of individuals on the utility of the commercial video data, at the same time making no attempt to evaluate the validity of any of the statements it cites. CRS has not studied the utility video database, nor has it ever taken a position on the Postol-Lewis methodology.[49]

The primary technical criticisms of the Postol-Lewis analysis may be summarized as follows: (1) the videotapes do not constitute scientific data; (2) successful kills will almost always appear with the Patriot video fireball located behind the Scud warhead; (3) the video-camera framing rates are too slow to obtain the spatial resolution needed to determine the Patriot interceptor Scud miss distance to a precision comparable to the Patriot interceptor kill distance; (4) the true three-dimensional miss distance cannot be determined from two-dimensional video data; (5) using the video jump distance as metric can lead to successful warhead kills being misclassified as clear misses because the video jump distance is severely shortened in certain viewing geometries; (6) a Scud warhead section after breakup would emit insufficient visible radiation to be seen on commercial videos until, perhaps, it descended to a very low altitude; (7) the object identified by Postol and Lewis as the Scud warhead in their analysis was not the actual warhead; (8) ground flashes are not proof of a Scud warhead explosion; (9) the large number of misses claimed by Postol and Lewis are not necessarily inconsistent with the Army's findings because three Patriot interceptors were fired on average against each engaged Scud and

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thus the videos can be expected to show a large number of missed intercepts.

ANALYSIS OF THE CRITICISMS OF THE POSTOL-LEWIS METHODOLOGY

With understanding of the Postol-Lewis methodology as summarized earlier, many criticisms (points 1–5) can be dismissed immediately. Others (points 6–9) require detailed discussion.

Point 1 confuses *scientific method* with *high-precision data*. The methods of science do not prevent the use of low-precision data provided the uncertainties and limitations of the data are respected. Indeed, science provides the tools for doing precisely this, and there are many cases in which skillful analysis of crude data has led to important scientific discoveries.

Points 2, 3, and 4 are correct statements, but they are all are irrelevant to the Postol-Lewis video analysis for reasons made clear earlier. In short, if the true three-dimensional miss distance is large enough, one can determine from a two-dimensional projection that an intercept attempt was a miss (no-kill) in spite of the coarse limit on spatial resolution set by commercial video-camera framing rates and the viewing geometry. Specifically, the Postol-Lewis methodology takes all such limitations into account correctly (conservatively) for all events they classify as clear misses. For fireball overlap events, they make no estimate of a miss distance and so points 2–4 are moot; these engagements are scored by other means.

The concern raised in point 5 refers to events in a corner of phase space where the video-camera is viewing the Scud trajectory approximately head-on. As discussed earlier, in this geometry three times the video jump distance could correspond in three dimensions to a distance smaller than the Patriot kill distance. (Basically the camera operator is standing at the target position and filming the Scud as it approaches head on.) However, if a Scud warhead was ever inside a Patriot fireball, it would remain so for multiple frames, and thus the event would be classified as a fireball overlap. A possible kill that occurred with this viewing geometry would *not* be misclassified as a clear miss even in the limit of zero video jump distance. Postol and Lewis report that only one of their 32 intercept attempts is close to this region of viewing geometry.

Points 1–5 as stated are invalid criticisms of the Postol-Lewis methodology.

Point 6 represents a fundamental challenge to the overall Postol-Lewis methodology. Unfortunately, it is not possible to make precise predictions of the surface temperatures that the Scud warhead section would acquire and thus predict the optical (visible) power that would result because many complex phenomena are involved. The spatial dimensions of the optical emission both before and after breakup greatly exceed those of an intact Scud or warhead section, and so what is being seen must be more than a hard body. A full explanation of the optical emissions (net optical power and spatial extent) would require detailed knowledge of trajectory parameters, missile materials, breakup patterns, and environmental conditions that are simply unknowable.

However, it is possible to estimate the maximum temperature of the warhead and the surrounding airstream using simple physical concepts. From a stagnation temperature estimate, it appears certain that warhead heating due to air friction alone can not be a primary source of the optical emissions seen in the videos. (Here we disagree with the assertion of Postol and Lewis made in their *Science and Global Security* paper that air friction alone could explain the observed optical emissions.) Heated air around and behind the warhead also cannot be the source of the extra luminosity because its emissivity is too low and the temperatures are too marginal for strong emissions in the visible. Most likely, combustion is involved in creating the strong optical emissions that make the Scuds so readily visible in the videos. For example, burning of leaking residual fuel up until the point where the warhead separates from the fuel tanks in breakup, accompanied by the combustion of debris and particle matter separating from the missile body and/or warhead section could make contributions to the visible signature. Following breakup and separation of the warhead section from the missile body debris, the list of possible sources for combusting matter (e.g., paint) that could be the source of enhanced warhead brightness is much more limited. Because the Scud warhead is reported to be nonablative, that possibility is ruled out. [50] Nevertheless, it is a fact that there is something visible that descends quite rapidly all the way to the ground in almost all the videos.

Does the leading visible object descend in the manner that is expected of a Scud warhead? That question brings us to the next point.

Point 7 is the assertion that Postol and Lewis have *consistently* misidentified the Scud warhead in their analysis. Their rebuttal to this assertion is based on a detailed fit to a sample of Scud trajectories and the drag coefficients derived therefrom (and also on the associated ground flashes discussed under the next point). They do not determine a drag coefficient for every engagement, but they argue that the behavior of the object they see emerging from Scud breakups, and identify as the Scuds warhead in the events they do

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fit, is similar to the pattern they see in the videos generally. (In Endnote 4 of Appendix B of their *Science & Global Security* paper, Postol and Lewis give a list of 12 video measurements of the time-to-ground following an intercept attempt. The corresponding Scuds are A1, A8, A9, A15, and A18 of our Table A. The average time-to-ground is 11.8 s. Two other intercept attempts (Scuds A3 and A6) for which a time-to-ground can be measured from the videos but which Postol and Lewis consider to be "unusually low" altitudes are excluded from this average.) The argument goes as follows.

The relative importance of gravitational force to drag for an object moving through the atmosphere is measured by the object's ballistic coefficient $\beta = W/(AC_d)$, where W is the weight, A is the cross-sectional area, and C_d is the drag coefficient defined by the drag force equation $F_d = \rho v^2 C_d A/2$.[51] The time for a falling object to reach the ground from a given height depends on its initial altitude, initial velocity vector (magnitude and direction), and the ballistic coefficient. (We are neglecting lift in this discussion.)

Figure 4 shows the fall time as a function of ballistic coefficient for an initial altitude of 11.4 km and a typical Scud trajectory. The steep slope of the left-hand part of the curve shows that for low drag objects, the time to fall is essentially independent of the beta coefficient, as would be expected intuitively. The initial altitude chosen for Figure 4 is representative of what Postol and Lewis conclude is the typical range of altitudes (10-12 km) at which many first intercept attempts took place, with second intercept attempts typically occurring about 3 km lower. They report videos often show Scud breakups occurring between the first and second intercept attempts.

Figure 5 shows fall times for a variety of altitudes over a more limited range of ballistic coefficients. The curves in this figure are calculated for an approximate analytical model[52] that assumes the re-entry trajectory is a straight line, the atmospheric density is exponential (constant scale height), constant drag coefficient, and that gravity can be neglected.[53] Because the straight-line trajectory approximation becomes increasingly inaccurate for high drag objects (low β), the curves in Figure 5 have been cut off at $\beta = 400$ lbs/ft^2. This plot is useful for understanding the sensitivity of fall times and derived values of β to the altitude of intercept but not for precision fitting of trajectories.

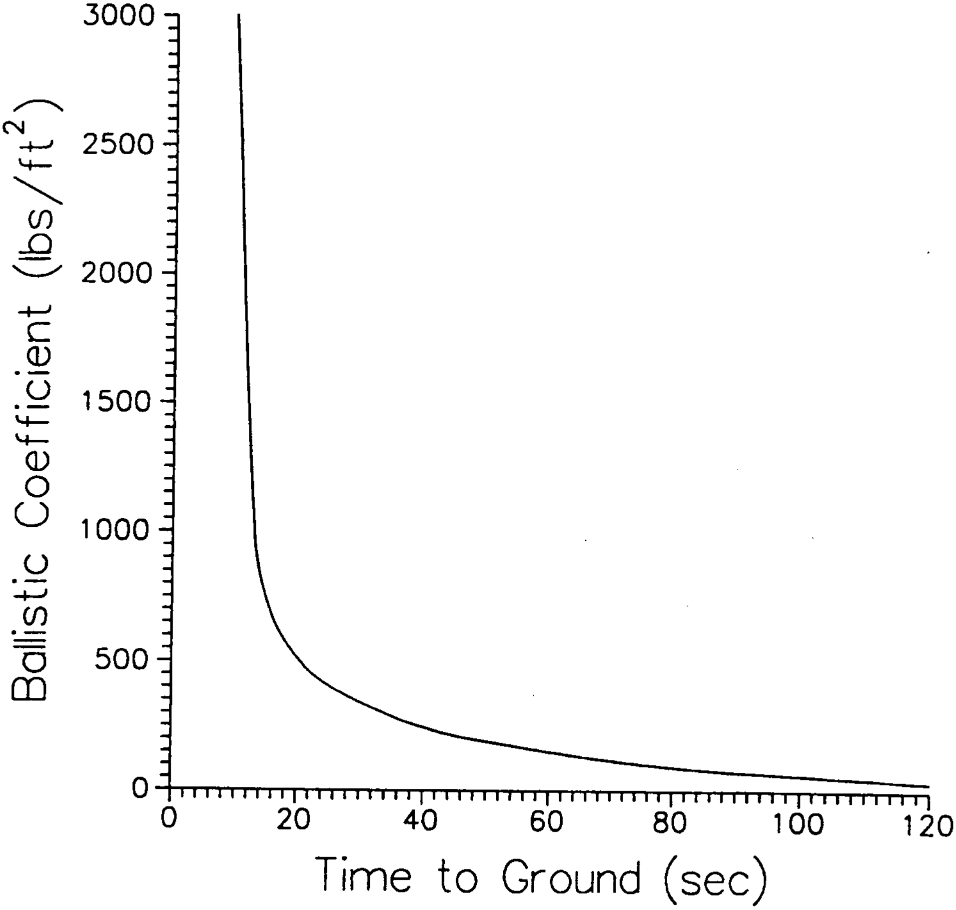

Figure 4: Plot of time to ground for an initial altitude of 11.4 km as a function of ballistic coefficient. The initial conditions correspond to a typical Scud (more properly Al-Hussein) trajectory. (Figure courtesy of Postol and Lewis.)

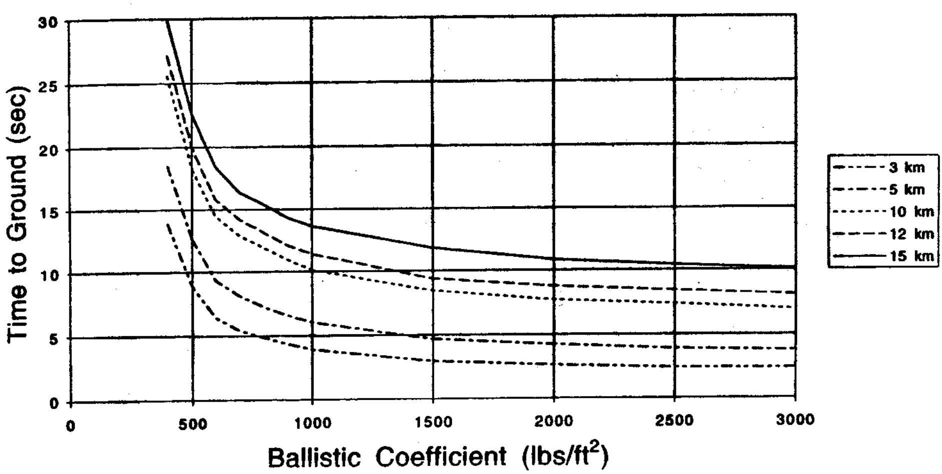

Figure 5: Time to ground as a function of ballistic coefficient calculated from an approximate model, which is described in the text. The figure can be used to estimate the sensitivity of ballistic coefficients fitted to time-to-ground measurements as a function of the uncertainty in the initial altitude. The curves shown in this figure are intended to show trends but are not to be used for detailed fitting of trajectory data. (Note, there is approximate agreement between the 12 km curve in this figure and the curve shown in Figure 4 that comes from a more detailed calculatrion.)

The videos allow a direct measurement of the fall time of any object that emerges from an intercept attempt for any viewing geometry, provided the object is tracked all the way to the ground. For the initial altitudes in the ranges indicated earlier, Postol and Lewis determine the ballistic coefficients for the leading visible object in several engagements. They find $\beta = (1{,}000 \pm 200)$ lbs/ft^2 where the error band reflects a range of initial altitude and initial velocity assumptions, and allows for possible variations of the drag coefficient. From Figure 5, we see that this error bound corresponds to an altitude uncertainty of about ± 2 km. (Note that the 12 km altitude curve in Figure 5 is in rough agreement with the more accurate curve given in Figure 4 for an initial altitude of 11.4 km.)

Postol and Lewis make theoretical estimates and cite experimental values from the literature to show that drag coefficients in this range are consistent with an object of the weight, transverse dimensions, and overall shape of a Scud warhead section. For an intact Scud and a cleanly separated, non-tumbling Scud warhead, ballistic coefficients are expected to be *approximately* $\beta_S = 3{,}000$ lbs/ft^2 and $\beta_{WH} = 1{,}200$ lbs/ft^2, respectively.[54] In contrast, the ballistic coefficients of an empty fuel tank or a section of the Scud missile body would be much smaller ($\beta = 100$–300 lbs/ft^2), especially if tumbling. For the latter class of high drag objects, the fall time from an initial altitude of 11 km is on the order of 25–50 s, in contrast to a fall time on the order of 10 s for a non tumbling warhead section. Such time differences are easily distinguishable using the video data.

The leading visible object in the videos falls at a rate that is consistent with it being a non-tumbling Scud warhead section.

We also note that the Postol-Lewis classification of events as "clear miss" and "fireball overlap" is robust whether the warhead is visible in the videos or not. This is because *all but two* of the clear misses reported by Postol and Lewis show the Patriot fireball well *behind* the leading visible object. If it is accepted that the *leading object is the warhead* (visible or not), the claim that Postol and Lewis have misidentified the warhead could result in a *decrease* in the number of fireball overlap events, but not an increase. All the intercept attempts classified by Postol and Lewis as clear misses would remain clear misses with an even greater miss distance, whereas some fireball overlap events might become clear misses.[55]

Point 8 can be addressed in a number of ways. As our discussion of the scoring reported in Tables A and B indicates, the interpretation of ground flashes plays a major role in the Postol-Lewis scoring. If it is accepted that the Postol-Lewis identification of warheads is correct (or merely that the warhead remains in general proximity of the leading visible object) the Army reports on the total number of duds is highly relevant. When a Scud warhead reaches the ground it either explodes or it is a dud. (A greatly reduced yield is also a possibility, but the Army reports only two cases of this in the Gulf War.) Hence, except for duds, all intact Scud warheads that reached the ground must have exploded on impact, and thus all cases in which the warhead is tracked all the way to the ground contain video imagery of the warhead detonation.

In information provided to the HGOC, the Army reported that a total of four duds were recovered during the war, two in Saudi Arabia and two in Israel. The first of the four duds landed in Israel prior to Patriot deployment. The other three duds were on Scuds engaged by Patriot. Postol and Lewis have video imagery of one of these[56] that tracks the leading visible object all the way (or almost all the way) to the ground. *There is no ground flash.* In the nine other engagements listed in Table A in which the videos track the leading visible object all the way to ground impact, a ground flash is observed.

Are the observed ground flashes consistent with what would be expected to be seen on a commercial video of a Scud warhead explosion (detonation) viewed from a distance? Unfortunately, the subject of optical emissions from the detonation of a high explosive does not lend itself to simple calculations. Details matter. We doubt that the conditions inside a Scud warhead could ever be known well enough to predict the resulting optical emissions reliably, however sophisticated the model and code. Nevertheless, some general remarks can be made.

Video imagery taken by a distant observer is unlikely to capture the very high temperatures (~5,000 K) that occur inside a piece of high explosive as a detonation wave sweeps through it (typical velocity ~ 8 mm/μ s) even when a clear line of sight to the impact point is available. There are two main reasons for this. High explosive material and its detonation products are optically thick (opaque). The very high internal temperatures associated with detonation would therefore be hidden from an external observer looking at even a bare charge of high explosive except when the detonation wave is close to the surface. If the charge were inside a metallic case or other opaque container, none of the optical emissions characteristic of the internal detonation temperatures could get out prior to the rupture of the case or container. After rupture, the air surrounding the charge (bare or encased) will be shocked by the expanding high explosive detonation products. In some cases, this shocked air can reach temperatures as high as 10,000-40,000 K, but only over a brief portion of the expansion. Air at such temperatures is a strong optical emitter, and the resulting emissions are referred to as "superluminescence." However, these super high temperatures last for only a fleeting period of time because the shocked air expands in three dimensions causing peak temperatures to drop rapidly. Estimates of the duration of shocked air temperatures exceeding 5,000 K are ~ 10 μ s to 100 μ s. The presence of the warhead case would probably mask the superluminescence during much of this interval. Given that the time between frames for a commercial video camera is 33 ms, at most only one frame could ever catch the superluminescence.

The ground flashes identified by Postol and Lewis as the signatures of Scud warhead detonations persist for several frames, that is, for ~0.1 s, with the flash brightest in the first frame in which it appears. [57] Although these emissions cannot be due to superluminescence, they are consistent with the optical emissions expected from a Scud warhead due to postdetonation afterburning. We give a brief discussion.

The Scud warheads used by the Iraqis were armed with approximately 240 kg of Tritonal, a popular explosive consisting of a mixture of 70% TNT and 30% metallic Al in a fine particulate (dustlike) form.[58] The addition of the aluminum adds considerably to the net yield because the reaction of aluminum with oxygen is highly exothermic. Much of this additional energy release occurs *after* the detonation process has expired because Tritonal is oxygen poor. Any aluminum and residual high explosive constituents that do not react all the way to CO_2 or H_2O during the detonation phase will undergo afterburning with atmospheric oxygen. Afterburning can be expected to be the primary source of the visible optical emissions from Scud warhead detonation. Afterburning durations on the order of ~0.1–1 s are expected with temperatures in the 1,500–2,500 K range. The turbulent mixing of the gaseous high explosive products with the atmosphere supports the continued combustion. The resulting fireball and optical emission is highly nonuniform and asymmetric. This is not observed in the commercial videos, probably due to camera limitations such as saturation of the video detection array and electronics.

An accurate determination of the color temperature of the ground flashes would be helpful. Unfortunately, this does not seem feasible using the commercial videos from the Gulf War. In addition to the fact that these instruments were uncalibrated, there could easily have been color distortions introduced by the camera's automatic gain control system, by atmospheric effects such as Rayleigh scattering, or other phenomena. Any such effects would bias the color temperature.

Are there credible alternative explanations of the ground flashes *other* than detonations? Could the optical emissions result from residual fuel that reached the ground and burned on impact? Given the total of 18 ground flashes in the videos listed in Tables A and B, the transport mechanism for bringing fuel to ground would have to have been a very regular event. For six of these ground flashes, there is evidence of extensive ground damage, implying something more than a combustion process was present. Warheads that cleanly part from the Scud body following breakup would quickly separate from the fuel tanks, which would fall much more slowly. An intact Scud or a Scud that underwent a partial breakup with a fuel tank remaining attached to the warhead section could carry residual fuel all the way to the ground, but except for the three known duds, all warheads must have detonated on impact. Thus, the burning fuel mechanism fails as an alternative explanation. No interpretation of the ground flashes other than detonations has been put forth that is consistent with all the data contained in the commercial videos and public record.

The ground flashes seen in the videos are consistent with the optical emissions expected from the postdetonation phase of Tritonal, the explosive used in Scud warheads.

Point 9 was raised soon after Postol and Lewis published their analysis of the videotapes. Criticism at that time focused attention primarily on the validity and significance of the Postol-Lewis scoring of intercept attempts as clear misses and fireball overlaps as given in Table A. It is correct that the videotapes would show a large fraction (two-thirds or more) of Patriot interceptors missing their targets for a ratio of interceptor missiles to Scuds of three or more, given a perfect defense. But this observation does not address the key issue of the Patriot engagement success rate. To determine whether the Postol-Lewis scores for Patriot *intercept attempts* are inconsistent with the Army's scores for *engagements* would require the use of a model that includes the probability of kill for an individual Patriot interceptor, the number of interceptors launched against a Scud, and assumptions concerning the independence of individual intercept attempts or, alternatively, detailed information about the dependencies of the probabilities. Instead of introducing such a model, it is far better to compare engagement scores directly, as Postol and Lewis do and as we display in Tables A and B. Engagement scores are the quantities of ultimate interest.

We show below that even without knowledge of the Army's scores for individual engagements, a contradiction exists between the official success rates for all engagable Scuds and the Postol-Lewis results for all scorable engagements in the video database without any need to appeal to statistical arguments.

Postol and Lewis report engagement scores for a total of 29 engagements, the 17 of Table A and the 12 of Table B. (Again, recall that two of the Scuds listed in Table A may be duplicates.) In the notation of this paper, the Postol-Lewis scores are 28 failures based on eleven distinct combinations of data (F1–F11), and one (O1) that would have been a failure (F10) if it was certain that the Scud was within the defended area. The weighted average of the final, official Army scores for Saudi Arabia and Israel is a 59% overall success rate. For a total of 44 engagable Scuds, this rate corresponds to 26 successes and 18 failures. The Postol-Lewis total of 29 failures is absolutely inconsistent with the Army's total 18 failures *even if every one of the engagements* not available on video was a Patriot success. If the two possible duplicates in Table A and the single engagement with an O1 score in Table B are omitted, one is left with 26 Postol-Lewis failures and the absolute contradiction with the Army's findings (18 failures) remains.

If one goes further and, in addition, throws out all Postol-Lewis engagements for which they do not have either extensive ground damage or ground flash evidence (that is discarding all F3, F6, F7, F8, and F11 scores[59] and also the O1 score, but keeping all F1, F2, F4, F5, F9, and F10 scores), Postol and Lewis are left with a central set of 19 engagements and 19 failures vs. the Army's total of 18 failures for all 44 engagable Scuds. Again a contradiction in the number of failures (19 vs. 18) remains, although the margin is small. However, to obtain this situation, all of the engagements dropped from Tables A and B and all of the engagements not available on video (collectively a total of 25) would have to been Patriot successes. This is highly improbable even using the Army's success rates.

It is possible that some or all of the four mission kills claimed by the Army are in the Postol-Lewis engagement set. If either of the two engagements scored by the Army as *mission kills by deflection* are in the Postol-Lewis set, the mismatch between their number and the Army's number of failures would decrease by at most two. Only in the most extreme case, where one keeps only the Postol-Lewis central core of 19 engagements does one escape an contradiction (19–2 = 17 vs. 18), but avoiding a contradiction requires that *all but one* of the other 25 engagements were Patriot successes, an extremely unlikely situation. It also requires that the Army evidence for the two deflections is sound.

The two engagements scored by the Army as *mission kill by reduction* of the Scud warhead yield to a low value (if correct) are unlikely to be engagements in the Postol-Lewis central core because low yield is inconsistent with extensive ground damage or a significant ground flash. If, to the contrary, one or both of these engagements are in the central core, the corresponding Army scores are suspect. Finally, it should be noted that dudding, deflection, or reduction to low yield are not the optimal kill mechanisms for a missile defensive system.

Ideally, one would want to compare the Postol-Lewis and Army scores on a Scud-by-Scud basis. However, this cannot be done because the Army engagement scores for individual Scuds remain classified. One subcomparison could be made: Scuds impacting in Saudi Arabia and those impacting in Israel. We leave that for the reader. We conclude:

The overall Postol-Lewis scores (0 warhead kills, 1 other, 26-28 failures) for 27–29 Patriot-Scud engagements (61%–66% of all Gulf War engagements) are profoundly incompatible with the Army's overall scores (22 warhead kills, 4 mission kills, and 18 failures) for 44 engagable Scuds. [60]

OVERALL CONCLUSIONS CONCERNING THE VIDEO ANALYSIS

We have not ourselves analyzed any of the videotapes, and so we cannot vouch for the quantitative measurements that Postol and Lewis performed on the video database or the quality of the supplemental non-video evidence they include in their analysis. We have, however, reviewed the Postol-Lewis methodology in great detail.

1) The methodology used by Postol and Lewis to analyze the commercial videos of Patriot-Scud encounters results in a physically consistent interpretation of all the phenomena observable in the videos together with all the other pertinent data available in the public domain. In spite of the limitations the video data present to the analyst, important information about Patriot performance can be learned from the videotapes. Claims to the contrary are without merit.

All of the data used by Postol and Lewis are in the public domain and so it is possible to reanalyze the data they used, but doing so would be a major piece of work. It may be that reanalysis by another party using slightly different judgments and criteria might result in a different score for a particular Scud engagement here and there, but it is extremely unlikely that the fundamental finding of Postol and Lewis that the Patriot system performance in the Gulf War was very poor would be changed.

(2) The success rates found by Postol and Lewis are insensitive to minor changes in their analysis and are demonstrably inconsistent with success rates reported by the Army for the performance of the Patriot system in the Gulf War.

While the Postol-Lewis analysis is based on simple physics, the actual phenomena involved are complex. Several features seen in the videos remain unexplained: the unexpectedly large video fireball sizes, the stronger than expected optical emissions from Scuds before and after breakup, and the detailed origin of the optical emissions seen in the ground flashes. Postol and Lewis had to overcome major obstacles to discover that useful information could be extracted from the videotapes and, over time, they learned how to do so while making an absolute minimum of assumptions. It is regrettable that the Army and Raytheon did not recognize that the commercial videos are a useful source of information about the performance of the Patriot system in the Gulf War. We conclude:

(3) The Army should have made use of the technical information available in the commercial video tapes in its analyses of Patriot performance in the Gulf War.

An integrated study involving both the video database and the Army's database would provide information about Scud trajectories, breakup altitudes, and related information that would sharpen the analysis of the video data of individual engagements. Conversely, the video data would sharpen the Army analysis in many cases, and it would provide insight into the validity of the Army's classification of its data into high-, medium- and low-confidence categories. Ideally, the Israeli data, too, should be part of an integrated study.

(4) The discrepancy between the Postol-Lewis and Army performance scores for the Patriot could be resolved by an integrated technical study combining the commercial videos and the non-video data from the public domain used by Postol and Lewis together with the (classified) ground impact / Patriot unit database used by the Army in its studies.

If the Army database and the second Army study report and supporting documents were declassified, a fully integrated study could be done, but even then it would be a major undertaking. If declassification of the complete database and documents is not possible, declassification of the Army scores on a Scud-by-Scud basis (e.g., each engagement) along with the confidence levels for each of these scores (high, medium, or low) would be extremely helpful in pinpointing the differences between the two analyses.

(5) Declassification of all or parts of the technical database used by the

Army in its second study of the performance of the Patriot in the Gulf War would help resolve existing questions about that study and be in the long term interests of the Army. Declassification of the Army scores on a Scud-by-Scud basis would be a useful first step.

LESSONS TO BE LEARNED

We believe there are several important lessons to be learned from the long and arduous debate over Patriot performance in the Gulf War. First, some comments and observations.

Patriot units now deployed in Korea, Israel, Saudi Arabia, and elsewhere include upgraded software, fusing, and other changes designed to enhance performance over the PAC-2 units employed in the Gulf War. The improved Patriot units are referred to as PAC-2 QRP (Quick Reaction Program). Consequently, Patriot performance in the Gulf War cannot be extrapolated to the performance of the PAC-2 QRP system without a detailed technical understanding of the system changes, which we do not have.

The Patriot system is scheduled to receive an entirely new interceptor called ERINT (Extended Range Interceptor) developed by Loral Systems. The new interceptor will use a dual K- and C-band radar seeker for end-game hit-to-kill homing. The resulting system when deployed will be called PAC-3 and will constitute the ground-based lower tier of the U.S. Theater Missile Defense architecture for a long time. Nothing we have studied bears directly on the performance of PAC-3/ERINT or any other future missile defense system, but it can be expected that the targets encountered by new missile defense systems will offer surprises, as was the case for the Patriot during the Gulf War.

Lesson 1

The intense and protracted debate over Patriot performance in the Gulf War together with disputes that continue today over the performance of other high-technology weapons systems in the Gulf War[61] demonstrate that it is a mistake to have the Program Office and the manufacturer of a new weapons system be the only parties that study the performance of that system post war. Organizations involved in procuring, developing, and manufacturing a weapons system simply have too much at stake and too many conflicts of interest. It is unrealistic to expect these parties to stand back and take a dispassionate look at all the evidence, no matter how well intentioned or technically proficient they may be. This lesson is not new; checks and balances are a necessity.

In analyses of a weapons system conducted during a war, it is critical that those that know the most about the systems be strongly involved. During the Gulf War, the Army and Raytheon Company made a number of changes on very short turnaround times to adjust Patriot software to the multiple, closely spaced set of targets that result from the breakup of a Scud, the helical trajectories of Scuds after breakup, ghost targets, and other effects that impacted the performance of the Patriot system. The quick response was truly impressive, as was the surge manufacturing of PAC-2 interceptors achieved by Raytheon. Nevertheless, there are reasons for concern.

It appears that the Israelis did a better job during the war in gathering and analyzing supplemental data relevant to Patriot performance than did U.S. personnel. In part it was probably easier because the Israelis were at home in contrast to the Americans who were operating in Saudi Arabia under a number of restrictions imposed by the host country's government. The more compact and urban nature of Israel probably helped as well.

The gathering and analysis of data cannot be the highest priority for weapons system operators during combat. Their job is to operate combat units as trained and to keep them on line to the maximum degree possible. There is every indication that U.S. Army operators of Patriot units in Saudi Arabia were dedicated and very effective in their jobs. Any shortcomings in the performance of the Patriot system in the Gulf War were not the fault of the operators. However, the Israeli data gathering and analysis activities during the war suggest an underlying lesson.

Lesson 2

It may prove wise to assign personnel with technical backgrounds as part of the regular detachment of high-technology weapons systems, but with responsibilities distinct from those of regular operators. The duties of the extra technical personnel would be to collect and preserve data relevant to system performance during combat. When the need arose, such personnel would work with civilian or other military experts to collect and analyze performance data and identify fixes. While data recording is voluminous and automatic in most modern weapons systems, there will always be surprises. In such circumstances technically trained personnel can respond to unexpected opportunities, gather special data, and make insightful recommendations. If staffing is such that no one's lead responsibility is technical surveillance of system performance, it is certain that no one will have time for that task in combat.

Lesson 3

The traditional linear development model for weapons systems sees a one-way progression through design, development, testing, and deployment, with the testing phase being the last step where significant technical involvement occurs aside from upgrades. For modern weapons systems, the linear model with a sharp separation between the testing and deployment phases is a false one. Most modern weapons systems are highly complex and, in many cases, impossible to test under realistic wartime conditions. The performance of these systems in combat should be seen as an extension of the testing phase. (In reality this is not new, nor is it unique to high-tech weapons.) If this view of the development process is accepted, it follows that modern weapons systems need to be accompanied by special technical personnel with duties, time, and access to data that will enable them to respond effectively to unanticipated events. If the U.S. military is not allowing for this now, it should give serious consideration to doing so.

ACKNOWLEDGEMENTS

The authors thank the many individuals who have helped over the long course of preparation of this article. They especially thank those who participated in the May 24, 1993 meeting in Washington, DC organized by the ad hoc panel: James Carter (Raytheon Company), Steven Hildreth (Congressional Research Services), David Israel (Ballistic Missile Defense Organization), Rick Jones (White Sands Missile Range), George Lewis (Massachusetts Institute of Technology), Theodore Postol (Massachusetts Institute of Technology), Steven Stanvick (Raytheon Company), Robert Stein (Raytheon Company), Peter Zimmerman (then at Center for Strategic and International Security), Israel Jacobs (General Electric Company/POPA) and Francis Slakey (American Physical Society/POPA). The authors also thank Richard Garwin, Caroline Herzenberg, Wolfgang Panofsky, Andrew Sessler, Randall Simpson, and Dean Wilkening who reviewed an earlier draft of this paper. Any remaining errors are the fault of the authors.

POSTSCRIPT

One of the authors (ODJ) has several reservations about the assumptions and technical analysis developed by Postol and Lewis that relate to the correctness of the identification of the bright object as the warhead in the Scud debris cloud, and that were then used to support other arguments. However, he supports the overall conclusions of this study concerning the utility of the video data and the basic methodology developed by Postol and Lewis in analyzing much of that data, as described in this report. A full resolution of the issues may require access to information not now in the public domain.

APPENDIX A: CHRONOLOGY OF THE AD HOC PANEL'S WORK

Members of the POPA Ad Hoc Panel on Patriot and Theater Missile Defenses were: Dan Fenstermacher, Daniel Fisher, Ruth Howes, O'Dean Judd, Roger Speed, and Jeremiah Sullivan (Chair).

The Ad Hoc Panel was appointed by the Panel of Public Affairs of the American Physical Society (POPA) in the spring of 1993 to look into the technical questions at the core of the debate on Patriot performance. POPA asked the panel to consider studies that the American Physical Society might perform to clarify public understanding of Patriot's performance and more generally of technical issues associated with future U.S. theater missile defense programs. The panel's work focused on clarifying the technical issues involved in the discussion and on identifying areas where parties to the debate disagreed on technical questions.

The ad hoc panel did not undertake a study of the performance of the Patriot system in the Gulf War—nor was it ever asked to do so.

Members of the ad hoc panel read the extensive literature in the debate as well as plans for Patriot improvement programs and follow-up on TMD systems and viewed the relevant video tapes. On May 24, 1993, the ad hoc panel convened for a daylong meeting in Washington, DC with technical representatives of almost all of the major participants in the Patriot debate. Following this meeting, the panel continued to work with participants in the meeting and other experts in an attempt to clarify and resolve outstanding technical issues.

On November 6, 1993, the ad hoc panel submitted a report to POPA making three recommendations:

1. The ad hoc panel recommended that POPA appoint a small team to prepare a short article about the debate over the performance of the Patriot system in the Persian Gulf War suitable for publication in a technical journal. The purpose of the article would be to inform the APS membership of the activities of the Panel on Public Affairs in respect to an important issue of public policy. (This article represents completion of that recommendation.)

2. The ad hoc panel recommended that the APS conduct an integrated study of the performance of the Patriot system in the Gulf War, if asked by the Administration, provided access was given to the classified ground impact/ Patriot unit database. A comparison of the engagements common to the Army and MIT studies would give insight on the strengths and limitations of the

database and methodology used in each. More definitive conclusions could be drawn than would be possible from each study alone. Clearly an integrated study could only be carried out with cooperation from the U.S. government, including access to the classified database and assistance from the Army in understanding it.

On March 22, 1994, POPA sent a letter to then Director, Defense Research, and Engineering (DDR&E) Anita Jones indicating APS willingness to do an integrated study of Patriot performance in the Gulf War in order to inform future TMD developers. A response received on May 17, 1994 from George Schneiter, Director of Strategic and Space Systems, stated that the Department of Defense felt that a further independent review of Patriot performance would not add significantly to understanding Patriot's capabilities and limitations during the Gulf War and would have little utility for future upgrades to the system.

3. The ad hoc panel recommended that the APS, through POPA, commission a major technical study that would address issues associated with the effectiveness of future missile defenses. A suggested focus of the study was "predicting and evaluating the performance of theater missile defense systems." To date no action has been taken on this recommendation. It remains under consideration by POPA.

Appendix B

Approximate Parameters of the Al Hussein*

	Missile with Warhead	Warhead
Mass dry (kg)	2,100	60
Launch mass (kg)	7,000	300
Length (m)	12.2	2
Diameter (m)	0.88	0.88
Drag coefficient-total	0.2	0.09
Re-entry velocity (km/s)	2.3	
Re-entry angle (degrees)	44	
Beta (kg / m^2)	17,000	5,500
Beta (lbs / ft^2)	3,500	1,100
Impact velocity (km / s)	1.6	0.7
Impact kinetic energy (MJ)	2,700	74
High explosive yield (MJ)		1,100

* Publicly available figures vary.[62] Above values should be treated as nominal.

Table A

Postol-Lewis Engagement Scores: Video Not Available of Intercept Attempts*

Scud	Location	Date	ON[1]	Intercepts[2]	TTG[3]	Impact[4]	Score[5]	Comments[6]
A1	Tel Aviv	Feb 09	I	3 CM, 0 FO	Y	GF	F1, F2	EGD (video and print)
A2	Tel Aviv	Feb 11	I	4 CM, 0 FO	N	NA	F3	No other intercept attempts
A3	Tel Aviv	Feb 12	I	1 CM, 0FO	Y	GF	F1, F2	EGD (video and print)
A4	Tel Aviv	Feb 19	I	1 CM, 1FO§	U	NGF	F7	Dud warhead recovered
A5	Riyadh	Jan 21	III	1 CM, 1 FO	N	NA	F6	No change in Scud appearance
A6	Riyadh	Jan 25	I	0 CM, 1 FO§	Y	GF	F5	Other Patriot??
A7	Riyadh	Jan 25	II	2 CM, 0 FO	Y	GF	F1, F2	EGD,office building destroyed, video
A8	Riyadh	Jan 26	I	1 CM, 1 FO	Y	GF	F5	
A9	Riyadh	Feb 03	I	2 CM, 0 FO	Y	GF	F1, F2	EGD (video)
A10	Riyadh	Feb 08	I	2 CM, 0 FO	N	NA	F3	No other intercept attempts; dud?
A11	Riyadh	Feb 11	I	0 CM, 2 FO§	N	GF	F4, F5[7]	EGD, school damaged (video)
A12	Riyadh	Feb 24	II	1 CM, 0 FO	N	NA	F3	A second Patriot self-destructed
A13	Dhahran	Jan 20/21	II	1 CM, 0 FO	N	NA	F3	No other intercept attempts likely
A14?	Dhahran	Jan 20/21	III	0 CM, 1 FO	U	NGF	F6	No change in Scud appeareance
A15	Dhahran	Jan 23	I	1 CM, 0 FO	Y	GF	F2	Also 1 PFB behind cloud and 1 PSD
A16	Dhahran	Jan 26	I	3 CM, 0 FO	Y	GF	F2	Also 1 PFB behind cloud
A17?,#	Unknown	Unknown	-	1 CM, 1 FO§	N	NA	F8	Change in Scud appearance

? Possible duplicate event.
IR video shown on commercial television; original probably of Israeli origin.
§ Change of appearance on video provides evidence that Scud was hit.

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1 ON = Ordinal Number, I = first Scud of that day to city, II = second Scud of that day to city, etc.

2 Postol-Lewis classification of observed interception attempt: CM = Clear Miss, FO = Fireball Overlap.

3 TTG = Tracked To Ground; Y = Yes, N = No, U = Uncertain (but tracked most, probably all, of the way to the ground).

4 GF = Scud tracked to impact and ground flash observed and interpreted as warhead detonation; NGF = Scud tracked to impact and no ground flash observed; NA = video data of Scud at moment of impact is not available.

5 Author's notation for the Postol-Lewis scores for the net engagement of a Scud: S = Success (Scud warhead destroyed or known to be dudded by action of Patriot); F = Failure, with F1 = no FO + yes EDG; F2 = no FO + yes GF; F3 = no FO + evidence that no additional intercept attempts occurred; F4 = yes FO + EDG, F5 = yes FO + yes GF; F6 = yes FO + no change in Scud appearance or trajectory; F7 = yes FO + dud Scud warhead recovered but no publicly available evidence dudding caused by Patriot; F8 = yes FO + yes change in Scud appearance with no change in Scud trajectory. The abbreviations are: FO = Fireball overlap, and GF = Ground Flash.

6 Comments based on information provided by Postol and Lewis. EGD = Extensive Ground Damage; PSD = Patriot Self Destruct (ground strike or premature detonation); PFB = Patriot Fireball.

7 The only available video of the engagement has been cut between the second intercept attempt and ground flash, making it impossible to be certain the intercept attempts and ground flash segments refer to same Scud engagement.

Table B

Postol-Lewis Engagement Scores: Video Not Available of Intercept Attempts*

Scud[1]	Location	Date	ON[2]	TTG[3]	Impact[4]	Score[5]	Comments[6]
B1	Tel Aviv	Jan 22	I	N	NA	F9	2 PL seen; Scud not seen; EGD (video)
B2	Tel Aviv	Jan 25	I	Y	GF	F10	X PL seen[7]; Scud seen[8]
B3	Tel Aviv	Jan 25	II	Y	GF	F10	X PL seen[7]; Scud seen[8]
B4	Tel Aviv	Jan 25	III	N	GF	F10	3 PL seen; Scud not seen[9]
B5#	Tel Aviv	Jan 25	IV	N	GF	01	3 PL seen; Scud not seen[9]
B6	Tel Aviv	Jan 26	I	Y	GF	F10	2 PL seen; Scud seen after descending below clouds
B7	Haifa	Jan 23	I	N	GF	F10	4 PL seen[10]; Scud not seen; GF distant
B8	Riyadh	Jan 21	I	Y	GF	F10	0 P seen; Scud seen only at end of flight
B9	Riyadh	Jan 21	II	Y	GF	F10	2 P seen; Scud seen; 1 PFB behind clouds; 1 PSD
B10	Riyadh	Jan 28	I	N	NA	F11	2 PL seen; Scud seen initially, then lost in clouds
B11	Riyadh	Feb 24	I	N	NA	F9	2 PFB seen; Scud seen late only; EGD (school)
B12	Dhahran	Feb 25	I	Y	GF	F9, F10	0 P launched; Scud seen; EGD (US barracks)

* Scuds B1, B4, B5, B7, and B10 are additions to the Scuds listed in Appendix of the Postol - Lewis *Science & Global Security paper.*
# Scud may not have been within defended area.

1 No Patriot fireballs appear in these videos.

2 ON = Ordinal Number, I = first Scud that day, II = second Scud that day, etc.

3 TTG = Tracked to Ground, Y = Yes, N = No, U = Uncertain (but tracked most, possibly all, of the way to the ground).

4 NA = Coverage of impact not available on video; GF = Ground Flash

5 Authors' notation for the Postol-Lewis scores for the net engagement of a Scud: S = Success (Scud warhead destroyed or known to be dudded by action of Patriot); F = Failure, where F9 = yes EGD; F10 = yes GF; F11 = Scud seen at low altitude with no Patriots within interception range; O = Other, where O1 = GF seen, but it is uncertain Scud impacted in a defended area.

6 P = Patriot interceptor; PL = Patriot Launch; PFB = Patriot Fireball; PSD = Patriot Self-Destruct (ground strike or premature detonation); GF = Ground Flash; EGD = Extensive Ground Damage.

7 Number of Patriots associated with this engagement cannot be determined for certain from available videos.

8 Engagements B2 and B3 are on the same video clip.

9 Engagements B4 and B5 are on the same video clip.

10 There may have been more Patriot interceptors launched, but precise number cannot be determined from the available data.

NOTES AND REFERENCES

1. The precise number remains classified. The number 44 is probably accurate to within ± 2 and similarly for the breakdown by country reported later in this paragraph. Non-engaged Scuds were those launched prior to Patriot deployment, Scuds out of range of any operating Patriot unit, and Scuds assessed to be on non-threatening trajectories whether or not they were within the range of an operating Patriot unit. The Scud that hit the Dhahran barracks is also included among the 44 even though no interceptors were launched because of a software error. (The Army scores this event as a Patriot system failure.)

2. For a complete summary of official statements during the Gulf War through March 1992, see Appendix 2 of Hildreth, S.A.,"Evaluation of U.S. Army Assessment of Patriot Antitactical Missile Effectiveness in the War Against Iraq," *Congressional Research Service Report* (April 7, 1992). (Reprinted in the reference that follows). The origin of the above percentages is as follows: the first comes from March 13, 1991 testimony of an Army official to the House Committee on Appropriations that the Patriot successfully intercepted 45 of the 47 Scuds against which interceptors were fired. The second figure comes from combining the May 1991 Army success rates of 80% in Saudi Arabia and 50% in Israel with the Scud counts of 28 and 16 for these two countries, respectively. The third comes from the April 1992 Army success rates of 70% in Saudi Arabia and 40% in Israel with the Scud counts as before.

3. "Performance of the Patriot Missile in the Gulf War," Transcript of April 7, 1992 Hearings, Legislation and National Security Subcommittee of the Committee on Government Operations, House of Representatives, U. S. Government Printing Office, (1993), 65-426, O-93-1 (ISBN: 0-16-04242-5). In subsequent references, we will refer to this as the "HGOC report."

4. A basic summary of the Patriot system and its history is contained in the first part of Stein, R.M., "Patriot Experience in the Gulf War," *International Security,* Vol. 17, No. 1, (1992), pp. 199–225.

5. Page 4 of General Accounting Office, "Patriot Missile Defense: Software Problem Led to System Failure at Dhahran, Saudi Arabia," GAO/IMTEC-92-(February 26, 1992), states that, "The Patriot weapons control computer used in Operation Desert Storm is based on a 1970s design with relatively limited capability to perform high-precision calculations." The phrase, 'relatively limited capability,' is not quantified.

6. All of these figures are approximate. Values in the public domain differ by as much as ± 20 % in many cases.

7. We do not know whether every Scud broke up; it appears that most did. There is no video evidence of an intact Scud reaching the ground.

8. "An Army Assessment of Patriot's Performance in Desert Storm," (1991), (Classified). Precise title is uncertain; we will subsequently refer to this as the "first Army study."

9. "An Army Assessment of Patriot's Performance in Desert Storm," (1992), (Classified). Precise title is uncertain; we will subsequently refer to this as the "second Army study."

10. "PEO Responds to Patriot Criticisms," *Inside the Army*, (Dec. 9, 1991).

11. Pedatzur, R., "The Israeli Experience Operating Patriot During the Gulf War," testimony and prepared statement, HGOC Report, (1992), pp. 118–130.

12. Pedatzur, R., "Evolving Ballistic Missile Capabilities and Theater Missile Defenses: The Israeli Predicament," *Security Studies*, No. 3, (1994), pp. 521–570.

13. Pedatzur, R., Israeli TV Documentary, (21 Nov. 1993). Highlights of these interviews are reported in Tim Wiener, *New York Times*, (21 Nov. 1993); and *Newsweek*, (Nov. 1993).

14. Public Broadcasting System, "Frontline," television documentary series on the Gulf War, (1996), Jan. 8–10.

15. Atkinson, R., *Crusade: The Untold Story of the Persian Gulf War*, (Houghton-Mifflin Co. Boston-New York, 1993), pp. 277-281.

16. Postol, T.A.,"Lessons of the Gulf War Experience with Patriot," *International Security*, (1992),Vol. 16, No. 3, pp. 119–171.

17. Stein, R,M., "Patriot Experience in the Gulf War," *International Security*, (1992), Vol. 17, No. 1 pp. 199–225; Postol, T.A., "The Author Replies," *ibid*, pp. 225-240.

18. Zimmerman, P.D., "Testimony before the House Government Affairs Committee and National Security Subcommittee," testimony and prepared statement, HGOC report, (1992), pp. 149–176; Zraket, C.A., "Testimony of Charles A. Zraket," Testimony and Prepared Statement, *ibid*, (1992), p. 177–186.

19. Fetter, S., G.N. Lewis, and L. Gronlund, "Why Were Scud Casualties so Low?", *Nature*, (1993), pp. 361, 293–296. A more detailed report by the same authors is presented in "Casualties and Damage from Scud Attacks in the 1991 Gulf War," DACS Working Paper, MIT Defense and Arms Control Studies Program, (March 1993).

20. Hinton, H.L., General Accounting Office, "Operation Desert Storm: Data Does Not Exist to Conclusively Say How Well Patriot Performed," GAO/NSIAD-92-340, (Sep. 1992). Reprinted in HGOC report, p. 104-117, 1992.

21. Davis, R., United States General Accounting Office, "Operation Desert Storm: Project Manager's Assessment of Patriot's Overall Performance Is Not Supported," testimony and prepared statement, HGOC report, (1992), pp. 77–89. The prepared statement is available separately as GAO/NSIAD-92-27, (April 7, 1992).

22. Hildreth, S.A., Congressional Research Service, "Evaluation of U.S. Army Assessment of Patriot Antitactical Missile Effectiveness in the War Against Iraq," testimony and prepared statement, HGOC report, (1992), pp. 12–76. This reviews the first Army Study. It also gives a comprehensive history of the Patriot program and official statements concerning its performance. Also useful is an earlier document: Hildreth, S.A., and P.C. Zinsmeister, Congressional Research Service, "The Patriot Air Defense System and the Search for an Antitactical Ballistic Missile Defense, CRS Report," (June 3, 1991).

23. Garner, J.M., Maj. General, U. S. Army, "Statement of Major General Jay M. Garner," testimony and prepared statement, HGOC report, (1992), pp. 216–229.

24. The second Army study was completed just prior to the HGOC hearing, and consequently neither GAO nor CRS was able to comment on it at that time.

25. Garner, J.M., Maj. General, U. S. Army, letter to John Conyers, Jr. in

response to a request for additional information about Patriot performance; reproduced in the HGOC Report, (1992) pp. 277-293.

26. Hinton, *op. cit.*, (1992).

27. The GAO report gives percentages, not actual Scud counts. Specifically, the report states that 25% of all engagable Scuds are scored by the Army as "high confidence warhead kills." GAO separates this into 9% plus 16%, with the 9% being those scores supported by strong evidence and latter those with weaker support. Using 44 total engagable Scuds, the breakdown translates into 4 and 7 Scuds, respectively.

28. Postol, T.A., "Optical Evidence Indicating Patriot High Miss Rates During the War," testimony and prepared statement, HGOC report, (1992), pp. 131–145.

29. Lewis, G.L., and T.A. Postol, "Video Evidence on the Effectiveness of Patriot during the 1991 Gulf War," *Science and Global Security*, Vol. 4, (1993), pp. 1–63.

30. Postol and Lewis, private communications to authors.

31. The ranges 29-32 and 15–17 reflect the possibility of duplicate imagery for up to two Scuds in Table A.

32. During the long course of the preparation of this paper, Postol and Lewis have provided the authors with additional details of their methodology and answered numerous detailed questions about all aspects of their work.

33. In their *Science and Global Security* paper, "Video Evidence on the Effectiveness of Patriot during the 1991 Gulf War," Postol and Lewis include one additional engagement (location and date unknown) for which the video shows a single clear miss intercept attempt. The engagement is scored as a *possible* failure. We have omitted that engagement from Table A because the videos do not show the outcome of a possible second intercept attempt.

34. Table A and the subsequent Table B were prepared from a revised version of "Appendix A: Video Tape Summary" issued by Postol and Lewis on May 22, 1993 as an update of the corresponding appendix in their *Science and Global Security* paper. The update includes additional video tapes acquired from

CNN. Three Scuds listed in the original version of Appendix A of the Postol and Lewis paper (Riyadh, Jan 22 I; Dhahran, Jan 20/21, I; and Date and Place Unknown, I) are not included in either of our Tables A or B.

35. For Scud B5 in Table B, Postol and Lewis are uncertain whether the impact point was within the defended area.

36. The uncertainly range 27–29 comes about because the presence of the possible duplicates A14 and A17 in Table A.

37. We refer to the bright regions seen on the videos following explosion (fusing) of the Patriot interceptor as the "video fireball" to distinguish them from the actual fireballs that had to have been much smaller.

38. The unclassified photo was taken during a test at the White Sands Missile Range of the interception of a Lance missile by Patriot PAC-2. The fireball diameter is about 25 m using the missile size as a metric. The figure is reproduced in Appendix B of the Postol and Lewis *Science and Global Security* paper.

39. The reason the Patriot interceptor must fuse (explode) in front of the Scud is simple. For a (near) head-on collision viewed in Patriot rest frame, the Scud is moving faster than the Patriot warhead fragments. Hence, if the Patriot fuses behind a Scud, the Scud will always outrun the fragments. Equivalently, none of the Patriot fragments are backward moving in the Scud rest frame.

40. At missile test ranges, multiple cameras at different locations are used to overcome limitation (2). High speed cameras are used to overcome limitation (1).

41. One interpretation of the shape of this distribution is the following: (i) fireball overlaps correspond to cases where the Patriot interceptor fused on the Scud warhead section or nearby debris, and (ii) clear misses are primarily cases where the Patriot interceptor fused on debris trailing far behind the Scud warhead or self-destructed after failing to find its target.

42. A fourth dud landed in Israel prior to Patriot deployment.

43. In footnotes 51 and 52 of their *Science and Global Security* paper, they cite two other pieces of information to support their position: first, the Army did

not provide any physical evidence to the Conyers committee in support of the claim that Patriot caused the dudding; second, information from an Israeli source that the dud was examined and found to have a defective (as opposed to damaged) fuse. Clearly the score for this engagement depends entirely on the evidence for or against the dudding having been caused by Patriot. The authors have no independent information on the matter.

44. "Analysis of Video Tapes to Assess Patriot Effectiveness, (Rev 1)," Army Material Test and Evaluation Directorate, White Sands Missile Range, NM, (March 31, 1992). The report presents the results of a review of 140 video tapes supplied by Raytheon, which purchased the tapes from commercial television news services.

45. Lewis, G.N., and T.A. Postol, "An Evaluation of the Army Report 'Analysis of Video Tapes to Assess Patriot Effectiveness'," MIT Defense and Arms Control Studies Program, (Sep. 1992).

46. Zimmerman, P.D., "Testimony before the House Government Affairs Committee," testimony and prepared statement, HGOC report, (1992), pp. 149–176.

47. Zimmerman, P.D., "Patriot Effectiveness (Rev 1) and Other Subjects Concerning Patriot ATBM Performance During Operation Desert Storm," report to Congressman John Conyers, (Sep. 14, 1992).

48. Hinton, H.L., letter report to Frank Horton, Ranking Minority Member, Committee on Government Operations, House of Representatives, GAO/NSIAD, (Oct. 1, 1992).

49. Hildreth, S.A., private communication and presentation at the May 1993 Washington meeting of the ad hoc panel.

50. It is probably not possible to generate temperatures hot enough from air friction to support ablation, in any case.

51. By convention, the metric definition of β uses mass in place of weight in the above definition, and thus is actually a different physical quantity.

52. Regan, F.J., *Re-Entry Vehicle Dynamics*, American Institute of Aeronautics and Astronautics, (1984).

53. To get a feel for how serious an approximation is the neglect of gravity, note that the ratio of the magnitude of the drag force to that of the gravitational force is 10 : 1 for an object with a ballistic coefficient of β = 1,200 lbs/ft^2, a velocity of 2.1 km/s, and the atmospheric density at an 11 km altitude corresponding to an atmospheric scale height of 7 km.

54. See, for example, Hoerner, S.F., *Fluid-Dynamic Drag: Practical Information on Aerodynamic Drag and Hydrodynamic Resistance,* published by the author, (1965).

55. The two exceptions mentioned earlier in the paragraph show the Patriot fireball well ahead of the leading visible object and are thus unlikely to be reclassified as hits in this scenario.

56. Scud A4 in Table A. They believe that A10 is likely to be another of the duds recovered by the Army. The video tape does not track the Scud to the ground, however.

57. In their *Science and Global Security* paper (Endnote 30), Postol and Lewis report that only in rare cases was the camera close to the impact point and had a clear line of sight to that point.

58. Johansson, C.H., and P. A. Persson, *Detonics of High Explosives,* (Academic Press, 1970), Chapter 5.

59. Note that this step also eliminates the two possible duplicates in Table A as they are scored F6 and F8.

60. Recall, as discussed earlier, the number 44 is approximate, but believed to be accurate to ±2.

61. General Accounting Office, "Operation Desert Storm: Analysis of the Air Campaign," GAO/NSIAD 97-134, (June, 1997).

62. "Ballistic Missile Proliferation: An Emerging Threat," Systems Planning Corporation, Arlington, VA, (October, 1992).